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# PREFACE

This issue represents the first step in the transition from an annual to a quarterly volume of A. I. E. E. TRANSACTIONS. The amount of technical papers published annually by the Institute has been constantly increasing, and during the past year reached a volume that could not economically be bound in a single book. To avoid discarding a large number of acceptable papers in order to keep within the limits of a single book, it has been planned to issue the TRANSACTIONS quarterly, in pamphlet binding, which makes them eligible to entry as second-class mail. A limited number of the quarterlies will be bound in cloth to meet the demand of those who desire a more permanent binding, for which an additional price is charged. Aside from its mechanical make-up the quarterly TRANSACTIONS will be exactly like the former annual volumes as to their contents, which will consist, as heretofore, of those papers and discussions presented before the Institute that are judged worthy of being included in its permanent records. It is believed that the present plan will take care of the increasing publication demands for several years.

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# PREFACE

This is Number 3 of Volume 47 of the Quarterly TRANSACTIONS of the A. I. E. E. It contains the one unpublished Winter Convention paper, together with those presented at the joint meeting of the New York Sections of the A. I. E. E. and the I. E. S., held in May 1928, and the papers and discussions of the St. Louis and Baltimore regional meetings.

The third Steinmetz Lecture, by Dr. Robert A. Millikan, is here published for the first time.

This number concludes with the Annual Report of the Board of Directors for the fiscal year ending April 30, 1928.

The last Quarterly each year will contain a complete topical and author's index for the four Quarterlies.

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This is the final number of Volume 47 of the Quarterly TRANSACTIONS of the A. I. E. E., comprising the papers and discussions of the New Haven Regional Meeting (May 1928) and the 1928 Summer Convention (Denver, Colorado, June 25-29), as well as the president's address and technical committee reports presented at the latter. Papers from the regional meetings held at Spokane and Atlanta will appear in the January 1929 Quarterly.

"An Amplifier to Adopt the Oscillograph to Low-Current Investigations," Mr. Sigmund K. Waldorf's prize paper, is published here.

This number concludes with the topical and author's index to Volume 47.

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# Advance Planning of the Telephone Toll Plant

BY J. N. CHAMBERLIN[1]

Member, A. I. E. E.

THE advance planning activities of a large telephone company is a field of endeavor that perhaps is not very generally understood by those not intimately associated with the communication art. This may be due to many circumstances, the more probable of which is the fact that telephone service has grown to be one of the necessities of social and business life and, from casual observation, seems to differ but little in individual locations. In the small or large community, similar subscribers apparatus is in general use; wires and poles of like character are in evidence and service is apparently rendered in much the same manner. These observations are basically correct. In structural design and operating practises, however, widely different problems are encountered in the rendering of service in separate communities.

Satisfactory service to the customer and economic operation in all locations require continuous study of both the present and probable future service demands, operating practises and characteristics of the physical plants design. In the small communities or exchanges, as they are called, problems of less complexity are encountered than in the metropolitan areas. The solution of these, however, whether they be large or small, are important functions of successful operation. Small exchanges grow and change in character and the telephone company must so plan its activities as to meet satisfactorily the future conditions as they may present themselves and at the same time, provide a financially sound structure in the rendering of a universal service. As a community develops and more service is rendered, more than proportionate amounts of capital and labor are required in providing the service for each additional customer. Interconnecting devices or switchboards are limited to a definite number of subscriber's lines. When the switchboard's capacity is reached, new offices or replacing switchboards of larger size are required. The number of operators employed is dependent upon the amount of service rendered and as service demands increase, more operators are employed. Pole line, wire, and cable are installed as needed to meet the expected future requirements of customers. The character and extent of this part of a telephone structure are governed by the size and density in population of the area served.

The average individual, not fully informed in the complexity of telephone equipment or the details of operation, is very apt, in his appraisal of the business, to use as a unit of measure, the telephone instrument. He fails to realize that, in a telephone system, separate and complicated pieces of equipment are permanently assigned on the switchboard to individual subscriber's lines and that large amounts of equipment and apparatus are required for the establishment of an independent channel of communication for each pair of talkers. The telephone instruments, channels of communication and switchboards are the mediums through which service is rendered. Therefore, the three components rather than any individual one should be used as a unit in a general analysis. Service, on the other hand, is what is being offered under the various tariffs and it, rather than any of the physical properties, is a more correct measure of value. If service is restricted as to hours, distances and types, the cost of rendering it lessens; likewise its value to the user.

The term "telephone plant" very aptly describes the structure by which communication service is rendered. It is ever varying in its charactristics and must grow in size and nature in a manner consistent with the demands resulting from the population within the area served. When people move into or within a community and want telephone service, the company must be prepared by the extension of its lines to give the service. As compared with other utility fields, the telephone business is somewhat unique in that applicants for service are not the only ones interested in obtaining it. The value of the service to those who already have it, is of course increased by the number connected with the system. Also the service rendered must always satisfy two individuals rather than one and must be available at such time of the day or night and for such duration as the customers, themselves, may elect.

During the pioneering days of the telephone business, little realization could be had of the development of the art to the state in which we find it today. To attempt, at the present, a detailed prediction of future attainments would result in but individual theory and is in no way herein attempted. Effort is to be made to simply set forth, in a very general manner, some of the fundamentals that are used today in advance planning, particularly as they concern long distance telephone service. In doing this, it will be necessary frequently to refer to some of the fundamentals underlying local or exchange plant planning, as such activities are intimately related to the planning of long distance service.

While similar to other structures in many ways, a long distance telephone plant is quite dissimilar, especially in regard to the ever present indeterminate demand that may, without any appreciable warning, be placed upon it. Local disasters and climatic disturbances repeatedly give rise to heavy service demands. These can, in no way, be anticipated as to time or importance. Their occurrence, however, must be expected and means provided in a general way for caring for these occasional surges in demands for service. Seasonal loads resulting from accelerated business activities occur at different times of the year in widely separated localities. The demand for service to and from recreation resorts during the summer months presents another rather indeterminate demand for service. These latter loads, as they are termed, can be better anticipated than the former as their annual recurrence can be made a matter of record and their characteristics closely studied.

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*Presented at the Pacific Coast Convention, Del Monte, Calif., Sept. 13-16, 1927.*

The linking together of two separate communities of meager population, as was repeatedly done in the past, is incomparable with the demands for the network of circuits made upon the telephone company of today by the ever growing metropolitan and suburban areas. Closely allied to the demand resulting from increased population is the growing demand as a result of the increased use of the telephone in business and social activities.

Experience has indicated that the telephone service grows much more rapidly than the population because of the necessity of meeting the service demands of not only the new population but also the increasing demands of the existing population. The term "population" as herein used denotes families, rather than a per capita population, it being obvious that such a unit is more closely related to communication service requirements than would be a per capita unit.

It is, therefore, a function of good telephone management to estimate population increases as accurately as is possible in advance in order that facilities may be extended with confidence that the future service demands will be satisfactorily met and that they will be handled along basically sound lines and with maximum economy. This requires what are termed "commercial surveys" or "development surveys" which are detailed estimates of future expectancies. The compilation of these surveys demands a large amount of field work, the tabulation of existing statistics and forecasting of the probable changes in amounts and distribution of the future population. Analyses are made of the amount of the past growth and of the reasons for this growth. The factors affecting future growth are considered and evaluated, and estimates made of the most probable future population growth.

As any estimate of future population may be in error, due to occurrence of some unpredictable event, it is highly essential that the management be ever on the alert to observe the first indications and the importance of changing circumstances and conditions. Selected and highly trained personnel, therefore, are continually employed in analyzing the economic and business conditions of the community being served and are closely studying the details of the probable moves of population within and between both urban and suburban areas. Such prophecy as an estimate of the probable redistribution of the population as will result from better roads or improved transportation facilities between communities is a typical example of this development engineering. Another example and one which is highly important in local or exchange line development survey activities, is the forecasting of the effect that will result from the constant change of individual properties from residence to apartment house and business purposes.

The estimates of future population are made of individual communities for a major portion of the area served and forecast the probable population for several periods into the future. These estimates picture the size, distribution, and character of the future market for telephone service. Additional estimates of the service demands from this market must then be made so that the final estimates may indicate the probable number of telephones that will be required at different future periods. As both individual and party line service are usually offered in an exchange area and telephone plant investment and operating costs vary in the rendering of the several grades of service, it is necessary to proceed further with the prediction of the estimated "telephone development" by classifying it into the various types of service rendered. After this has been accomplished these data are transcribed in numerical form to large scale survey maps covering the area being studied. These maps are called "telephone line distribution maps," and serve to indicate the density and approximate location by small areas of the total number of anticipated subscribers lines.

When the features of the development survey necessary to prepare the line distribution map have been concluded for individual communities, it is necessary to then make predictions as to the amount of service that will result from the estimated telephones. In telephone language this means the determination of the "calling rate" or average use of the service per customer's station. In small communities this is not a feature of major concern. In the metropolitan areas, where several operating central offices are maintained, it is a highly important function in developing the detail design of the future plant structure.

Interrelated and associated with the study of calling rates in a multi-office exchange area is a further activity which has to do with the forecasting of the direction of the flow of service between the several operating areas within the exchange. Between adjacent central office districts there usually exists a different community of interest among the customers than between non-adjacent offices or between residence and business areas.

The ratio of the present telephone development to the population, location, average number of daily calls per customer's station, and the direction of flow of the past service is, of course, a matter of record. These statistics are extensively used in making predictions but in no way preclude the necessity for the exercise of sound judgment in forecasting the probable future trend of service demands and characteristics. Upon the results of these series of studies and forecasts, operating plans are adopted and construction details determined. It is therefore, apparent that this portion of advance planning work is a highly important part of telephone engineering.

In the exchange lines or local plant planning, these data are used to prepare basic plant layouts to be used as guides in construction and future extension work. These plant layouts, or "fundamental plans" as they are called, depict both present and anticipated future central operating centers, local service limitations, economic plant arrangements, and such other pertinent data as may be reasonably forecast. Their preparation requires a large amount of time and study by a personnel that has a thorough knowledge of telephone fundamentals. Detailed consideration in these studies is given to the determination of the ultimate number, size, and location of central offices. Comparisons are made of various types of equipment, operating methods, and construction details. The wire mileage required in concentrating the subscriber's lines as indicated on the previously mentioned line distribution map under different plans are determined, land values and costs of construction and maintenance estimated and studied before the selection of a plan is undertaken. In exchanges requiring but one central office, these tasks are comparatively simple. In the multi-office exchange, however, and those approximating such size, many additional factors, such as trunk and tie lines between central offices, present themselves as influencing factors in arriving at an ultimate decision. Many other features of importance are concerned in these fundamental plan studies but cannot be dealt with here in the time allowed for the subject in hand.

In long distance or toll line advance planning, these same data are used in the formulation of a long range basic toll line plant layout or toll fundamental plan. In these latter studies, however, it is necessary to analyze, among other things, the flow of calls between, rather than within, individual communities. How service between separate and distant areas is to be handled, where interconnection between circuits and recording is to be done, and how many circuits will be required to satisfactorily serve the long distance service demand over future periods of years, are the desired conclusions to be obtained from these studies.

The item of cost in relation to service finds its fullest application in these fundamental plan activities. Advancement in the art is to be anticipated and the cost of all progress must be judicially interpreted and forecast. Technical development is of necessity an all important factor in the giving and extension of communication service. Its mastery, however, in no way excludes the study of economies; on the contrary, it creates economic problems that require extensive study and ultimate solution before general application can be made of any individual improvement.

Many different general plans of varying details present themselves for solution during the activities concerned in these studies. These must be independently worked out and comparisons made, both from the service and cost viewpoint, before conclusions are formed. This is done through the medium of engineering cost comparison studies which usually express in terms of equivalent present worths, the total costs of the different plans over an extended cycle of years. Special problems concerned with detailed features of individual additions to the plant structure, quite naturally cannot be intimately dealt with and fully set forth in a general study of basic fundamentals. These must be studied as they arise during current activities dealing with changes and additions to the plant and their solutions obtained through individual study.

The engineering cost comparison study, in which the initial investment, deferred investments, annual charges and credits for future salvage returns of different plans of comparable design are analyzed, is a most important element in future planning. The initial and deferred costs of the different plans are usually very readily obtained. The annual costs and salvage credits to be anticipated at the termination of the service life of the plant structure are more difficult of correct interpretation. They are, nevertheless, of equal importance in the solution. Similar to all analyses of future cost factors, these engineering cost comparison studies involve the making of definite assumptions of future anticipation. Due to the climatic and human elements, that continually affect the service life and maintenance expense of a large part of a telephone company's investment, it is highly essential that the assumptions in these studies be based upon an intimate knowledge of present and anticipated factors, and that proper decisions be made in appraising the results that are indicated at the conclusion of the studies.

It is very necessary in their interpretation, therefore, to give thorough consideration to many intangible elements. A few of these may be cited as follows:

1. The practicability of the several plans under possible future changing conditions.
2. The adaptability of the separate plans to existing plant units and to future technical advancement.
3. The new money required to put the individual plans into effect.
4. The weighing of assured immediate economies of one plan with the estimated future economies of other plans.

There is no simple method for determining exactly how many toll calls will flow to or from individual communities. The experience of competent engineers and a thorough study of past and present statistics and related forecasts is the best available guide in planning for the expansion of the service. Extensive records are kept of the average number of long distance calls placed per customer's station; of how the originating traffic of individual communities is distributed over existing circuits; of the time consumed in making the desired connection or interconnection, and the average time the circuit is held for conversation.

For the purpose of planning, schedules of the call carrying capacity of the circuits under different operating methods and under different conditions as regards service delays have been formulated. Their application varies with the length of the circuit, number of circuits in a group, and the ratio of direct calls-to-calls requiring built up connections. In planning for the future, these theoretical circuit capacity schedules are set up on a premise of a different degree of freedom from service delays, on account of no circuit conditions, occurring on a given number of calls. By a no circuit condition is meant that all circuits in a particular circuit group are in use at the time a connection is desired.

The determination of future circuit requirements over long term periods is carried on by the use of these schedules and the estimates of future traffic. In predicting the immediate necessity for circuit rearrangements and additions they are, however, modified to meet the circumstances under individual review. As operating conditions and local service demands result in a considerable varying of speed of service and circuit capacity between individual communities, it is necessary that intensive study be given to individual groups. Such matters as the size of the circuit group, the type of service to be rendered, the average length of conversation, and the distribution of the traffic through the hours of the day, must receive careful consideration.

A record is usually taken over a period of 20 business days during the month, in which the distribution of the traffic is representative of the conditions for which the plant is to be engineered. When encountering conditions that are not similar throughout the territory, this record is adjusted for the different seasonal conditions. As circuit groups do not experience their greatest traffic in the same month or maintain the same trend throughout the year, supplemental checks of the traffic volumes are made. Ordinarily additional circuits are provided less liberally for groups showing a traffic peak of relatively short duration than for groups carrying heavy traffic over periods of two or three months. These checks are also studied for the purpose of determining the possibility of overflowing traffic to groups having margins and of rearranging the circuit layout either temporarily or permanently to meet fluctuations.

These detailed studies of circuits and load characteristics have been used extensively in the past in determining the immediate and early necessity for circuit rearrangements and additions to individual groups. Today it is necessary to use them as a guide in the projection of future requirements over long periods of years. This is due to the changing design of long distance telephone plant and is made necessary by the installation of a large portion of the circuit facilities on a somewhat different basis than in former years.

Until a comparatively few years ago, practically all long toll circuits were of open wire construction; that is, individual wires separately attached to crossarms on the poles. These have been installed as required and were a natural development due to the small number of circuits required to handle early day long distance demands. The wires have very generally comprised two sizes, namely, No. 8 Birmingham wire gage, (165 mil.), weighing 435 lb. per mi., and No. 12 New British standard gage, (104 mil.), weighing 173 lb. per mi. These two types of uninsulated wire have admirably lent themselves to the many changes and improvements in the communication art. For many years the limits for the highest grade service with these conductors were approximately 400 and 200 mi., respectively. The development of associated equipment, however, has so increased the distance over which service may be rendered with these sizes of wire, that today finds them in general use over distances of thousands of miles.

The introduction of the inductance or loading coil on open wire circuits, many years ago, so reduced the attenuation loss of open wire circuits that satisfactory voice communication was greatly extended in range. Distance of transmission on open wire circuits was later further increased by the installation of the mechanical repeater into the circuit to be used in conjunction with the loading coil. Experience, however, soon indicated that improvement must be made in the uniformity of the amplification given by the repeaters in order to raise the intelligibility of the voice transmission to a higher standard. This led to the use of the vacuum tube repeater which economically and satisfactorily eliminated the limitations of the mechanical type repeater. As a result, the vacuum tube repeater soon replaced the mechanical type and is today exclusively used in voice amplification.

Improvements and modifications in the design of the repeater and reduction in its cost of manufacture have made it desirable and economical to use it more frequently on long-distance lines in lieu of the loading coil. At present, therefore, we find the use of the loading coil on open wire lines very generally restricted. In its place is found the vacuum tube repeater, with service range increased and quality of transmission improved.

The non-loaded No. 165 and 104-mil open wire circuit have also permitted the development and use of the higher frequency ranges in voice communication. Without distortion or sacrifice to the quality of the service, frequencies ranging up to 30,000 can be used on non-loaded repeatered open wire lines. The application of these higher frequency ranges to what are termed "carrier current systems," in voice communication, has extended the field of use of the open wire circuit many fold. In brief explanation of this statement, a typical open wire line, carrying four fully equipped ten pin crossarms, is capable of providing the following voice channels. Four crossarms supporting 40 wires of the standard configuration of 12-in. horizontal and 24-in. vertical separation, when properly transposed, produce 20 physical and 10 phantom circuits or a total of 30 voice-frequency talking circuits. By the proper coordinating or additional transposing of 8 of the wires on the top crossarm four carrier current systems can be superposed on the 8 wires. As each system is capable of producing 3 speech channels a total of 12 additional circuits is thus provided. Without any loss in the number of voice frequency circuits on the lead four similar carrier systems with like circuit possibilities can be superposed on eight wires of the third crossarm. This complete arrangement therefore increases the speech channels on a 40-wire line from 30 to 54 circuits or nearly one hundred per cent.

Carrier current telegraph systems of ten channels each can also be similarly superposed on the open wire circuits, thus in another manner greatly extending the use of open wire for communication service. At the present time it does not appear economical, due to the excessive expense of balancing the open wire for purpose of eliminating interference or "cross-talk" to superpose telephone carrier current systems of the three channel type on adjacent crossarms.

These three-channel carrier systems require highly expensive terminal equipment and well insulated and evenly balanced open wire lines. The economy of their installation generally speaking is confined to lines of 150 mi. and over in length. Often however, major reconstruction work on a pole line that would be required by additional open wire placements can be advantageously deferred by the judicious use of the carrier systems. Recent developments in high-frequency systems have resulted in a new system of one channel. This type is proving economical for superposing on open wire lines of approximately 50 mi. in length.

The rapidly increasing demands for toll service several years ago indicated many difficulties in providing for future long distance communication service on a wholly open wire basis. The number of open wires that can be placed upon a pole line is limited. The number of pole lines that can be constructed along highway routes is restricted and the costs of purchasing private rights-of-way for open wire lines is becoming excessive. These conditions prompted the development of some other practicable method of providing for the increasing number of toll circuits.

To meet this situation, effort was made to provide means which would permit of satisfactory conversation over long lengths of cable. In other words it appeared desirable to provide along one path a greater number of circuits of a type that require less space and structural support. In this endeavor highly successful results have been attained. Satisfactory conversation can now be given over an extended network of cable plant. Repeater operation appears to have solved the problem of distance and in so doing has made possible reductions in the use of copper to approximately 10 per cent of the amount used in open wire circuits of equal length. For example instead of the No. 8-gage open wire weighing 870 lb. per circuit mi. and the No. 12-gage weighing 344 lb. per circuit mi., the conductors, which are extensively used today in cable design weigh but 80 and 40 lb. per circuit mi. In the cable type of construction from 100 to 300 voice frequency circuits are provided in a cross sectional area of less than 6 sq. in. To accomplish this, relatively small gage wire must be used and some dielectric other than air must be provided for maintaining separation of the wires.

Two types of cable conductors present an economic balance at this time for general use. These comprise 16-gage wire, weighing about 40 lb. per mi. and 19-gage wire, weighing about 20 lb. per mi. These wires are each individually insulated by means of a spiral wrapping of paper ribbon of approximately 0.004 in. thickness and 0.625 in. in width. The wires are twisted into pairs, the pairs laid up into groups of 4 wires, termed "quads" and the "quads" stranded together and enclosed in a lead-antimony sheath of approximately ⅛ in. in thickness. In a large portion of toll cable installations it is found economical to provide a complement of both sizes of conductors in an individual cable sheath. This feature can be determined only after an extensive and detailed study of the use to which the individual circuits are to be placed. In a majority of instances comparisons must be made as to the economies of a larger gage with those of a smaller gage provided with a greater number of telephone repeaters, it being possible to obtain the same grade of circuits having given characteristics, by either size of conductor equipped with a different number of repeaters.

It is conceivable, although obviously impracticable, to design all circuit groups on a toll lead as individual units. Practical operation requires the centralizing of loading coils and repeaters at a minimum of locations. In the average cable installation loading coils are placed at regular intervals of approximately 6000 ft. and repeaters at approximately 50 mi. intervals. In locating these latter, consideration must be given to housing facilities as from one hundred to several hundred repeaters are usually installed at a given location. They must also be located in close proximity to the location dictated by electrical requirements.

Toll cable construction presents many advantages over open wire plant. It provides at one time an equivalent number of circuits that are offered by seven or eight open wire lines. The ever annoying foliage interference occasioned on open wire circuits passing through wooded sections is largely eliminated by cable construction. Of major importance also is the relief afforded from service interruption occasioned by sleet and wind storms and the resultant costs of the restoration of service.

Thorough studies of the economic design of toll cables are important before proceeding with an installation. Due to the many circuits provided at one time and the relative high cost of cable construction it is necessary in economic planning to design a cable to serve for an extended period of years into the future. This requires not only an intimate knowledge of the present use to which an individual cable is to be placed but also a well coordinated plan of its fitness to form an important unit in an ultimate cable network.

In long-distance wire communication, therefore, consideration is given in advance planning to the provision of three types of service facilities. Between the scattered and sparsely settled areas, the open wire circuit is at first provided. As demands for more service are encountered additional facilities are provided by means of more open wire or the superposing on existing wire of carrier current systems. Between the well developed and fast growing areas, however, where an extensive network of circuits is already in service the matter of planning for future additions is a decidedly different problem. Here is encountered the solving of many problems relative to the continuance of open wire construction versus toll cable installation.

Questions of route, both as to desirability and permanency of location are of major importance in designing additions and changes in the character of construction. In the early days of the telephone business this was not a matter of great concern. With electrical development in the power and communication fields and the gradual extension of both services, the problem of the coordination of the network of wires makes necessary an intimate study of the induced disturbances that may result when wires of either service are located in close proximity to wires rendering another type of service.

Many fundamental differences exist between power and telephone transmission systems. The former transmits large amounts of power usually at relatively low frequencies while the latter transmits speech waves through the use of a very small amount of electrical energy at a comparatively high frequency. Even with the use of relatively small amounts of electrical energy in wire communication, the economy of placing circuits close together and of superposing several channels of communication on each pair of wires, justifies and requires an elaborate scheme of coordination between the telephone wires themselves to eliminate mutual interference between channels. These requirements are closely related to those for prevention of interference from external sources. Induced disturbances from electrical circuits rendering other services, when in close proximity to communication channels, may seriously interfere with satisfactory voice transmission and cause interruptions to service, damage to plant, and hazard to personnel.

This subject of interference from other sources has been extensively discussed on previous occasions. Reference is made to it in passing for the purpose of indicating the continued importance of coordination work by those concerned in the advance planning of telephone and power long distance service. If the more general use of toll cable construction should eliminate the inductive coordination problem of today it would indeed be fortunate. Such attainment however, cannot be anticipated. Freedom through separation from other electrical circuits and the cooperation in the application of remedial measures by all wire using companies must continue to be effected in the planning, maintenance, and operating practises of the different electrical systems. In the advancement of such cooperative effort notable contributions have been made by the interutility joint committees, such as the General Joint Committee of the National Electric Light Association and the Bell Telephone System.

Other problems, not of an electrical nature, are concerned with the construction details of both open wire and toll cable installations. Pole structures must be designed to withstand not only the dead weight of the anticipated attachments but the storm stresses that may occasionally be experienced. These of course vary in different locations and are an individual field of study and research. Studies of this nature are not confined in particular to the telephone business but they are an important element in the work of rendering proper service. Sub-surface structures, such as conduits and splicing vaults form a large item of investment in all telephone companies plant. This type of construction is rapidly being extended, particularly in connection with extensive toll cable conditions. Underground conduits, into which cables may be drawn, offer reasonable permanency of location and freedom from fire destruction and the devastating effects of climatic disturbances. In order to obtain economies in underground construction however, it is necessary to provide for many years into the future; therefore well established fundamentals must underlie any major conduit installation. In this connection it differs from the other branches of advance planning work only in that it usually concerns the provision of a type of plant for greater periods into the future.

The results obtained by making the studies which have been very briefly discussed indicate the anticipated relative economies of the future plant structure under assumed conditions. It is necessary however, before undertaking any major plant work, particularly if large expenditures are involved, to formulate a well balanced and orderly construction program. This is a very essential part of advance planning. Materials and labor must be available at widely separate locations and at prearranged periods and all unfavorable reactions to the service while carrying on the construction program must be avoided. For purpose of indicating the scope of these planning activities and their results the following brief review is given of a portion of the Pacific Telephone and Telegraph Company's present toll plant structure and current extension program.

In the Northern California area of the Pacific Company's territory, comprising a majority of the communities in the State of California situated north of the Tehachapi Mountains, there are some 380 separate company operated exchanges. These vary in size from the small hamlet of a few inhabitants to the large cities of several hundred thousand population. Interconnecting and serving these localities with long distance telephone service are 178 main or toll center groups of circuits and 424 so called tributary circuit groups. At the present time most of these are in open wire construction. In planning for the future, quite naturally the major problems center around the larger and more rapidly growing groups. Correct solution of the future service on these groups however, cannot be obtained without thorough consideration being given to the tributary groups. This is being carried on by members of the Pacific Company's staff. Many circuit miles of open wire construction is included in the future program. Extensive carrier current systems are contemplated and approximately 1000 mi. of toll cable installation is being designed for the provision of service over the next 10 year period.

Within the past 12 months a 90-mi. section of this cable network has been completed between the San Francisco Bay area and Sacramento, California. The cable was designed to provide 295 voice communication channels for rendering service to Sacramento and points north and east. Liberal provision was also made for service to intermediate points. The cable is of 19 and 16 gage design, is equipped with loading coils at intervals of 6000 ft. and is provided with repeater service at the town of Crockett, located 30 mi. northeast of San Francisco. The repeater station is equipped at the present time with 100 repeaters and is designed to house approximately 200 additional repeaters over the next few years. This toll cable has been designed for extension northward and eastward at a future date, at which time it will form an intimate unit of a cable network extending very generally throughout the State of California.

In the 1000 mi. of toll cable network included in the present program, studies indicate the desirability of proceeding with the installation of approximately 100-mi. of cable per annum. A large part of this will be along existing open wire routes, although considerable relocating will be required and many underground sections will be constructed.

In the San Francisco Bay area there exists today an extensive toll cable network. This provides cable circuits to and between surrounding communities and toll entering facilities for the long distance open wire circuits radiating from the San Francisco Exchange. The continued maintenance and future planning of a large portion of this network presents an additional and independent problem, not previously referred to and not very extensively encountered in other localities. This has to do with the planning of a large amount of submarine cable plant.

San Francisco Bay is an extensive body of water, both in area and depth. To cross it at strategic points with communication service and place the necessary plant structures in reasonable permanent locations, requires the use of submarine cables of closed sheath lengths of from 10,000 to 13,000 ft. These cables must be maintained at depths ranging to 200 ft. In the crossing of the Bay from San Francisco to the East Bay communities, a water distance of approximately 4 mi., two 10,000 ft. sections are required to form an individual cable. The presence of Yerba Buena Island about mid-distant makes it possible to so sectionalize the cables into two units. This is a fortunate circumstance as advantage can be taken at the shore of the island to install cable loading coils.

In the short haul circuit groups rendering transbay service between the Bay area communities there are in use at the present time approximately 1400 circuits. Some conception of the magnitude of this number of voice frequency circuits may be obtained by realizing their equivalent number expressed in open wire. Were it possible to render this transbay service with standard open wire construction there would be required 24 individual pole lines each supporting 8 crossarms of 10 wires each.

Until a comparatively short time ago all circuits entering and leaving San Francisco, with the exception of one very short circuit required in their path the use of submarine cable. This was a very undesirable situation due to the ever present hazards to that type of plant and the serious service interruptions that usually accompany a submarine cable failure. Recent local developments and major toll underground cable extensions, have made possible a partial change in this regard, although it will continue to be necessary in providing future additional service to install and maintain a large amount of submarine plant and equipment.

In the advance planning of these submarine facilities attention is given to the judicious safeguarding of the plant and to the adoption of such operating methods and arrangement of circuits that will require a minimum number of submarine cables. As the volume of service over individual circuit groups and plant conditions permit, circuits previously interconnected at or switched through San Francisco, are otherwise routed. While the development of economies that may be anticipated from a change in circuit routings is an important part in the advance planning of other parts of a telephone plant, as previously referred to in the fundamental plan activities, it is of major importance in the planning of toll circuits across San Francisco Bay.

Many other and equally important features of telephone long distance advance planning could be set forth in this discussion. Those of an electrical and mechanical character have been often presented in various forms and therefore have been omitted. This has been done with no intent to stress the importance of any part of the activities concerned with the advance planning of long distance service but more in an endeavor to set forth briefly certain fundamentals of the work that are not generally realized by those not connected with telephone work. While classed a branch of the electrical profession, telephone planning and operation comprehend important elements not at all electrical in their character. Electrical phenomena and their adaptation to the art of communication are essential features, but of equal importance is the solution of problems unrelated to the electrical science. Successful management of a telephone company as a result of these circumstances, depends in part upon the study and application of electrical accomplishment, in part upon the analysis and forecast of economic conditions prevailing and anticipated in the area being served with communication service, and in part upon the solution of mechanical problems relating to the construction and maintenance of a plant structure, the whole combined to render an economic service and produce a fair return on the investment.

## Discussion

For discussion of this paper see page 20.

# Tandem System of Handling Short-Haul Toll Calls
## In and About Los Angeles

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### INTRODUCTION

IN telephone practise there are, broadly considered, two distinct methods of completing telephone calls between central offices, one by means of direct trunking and the other by means of tandem trunking. The fundamental difference between these two methods may be best obtained by referring to Fig. 1. It will be noted that direct trunking, as the name implies, requires a separate group of trunks from any one office to every other office, whereas tandem trunking provides for a single group of trunks from each office to a centralized point, known as the tandem center or office, at which are means for switching together any desired combination of trunks. Under the direct trunking plan, 30 groups of trunks are required to interconnect completely the six offices illustrated, while under the tandem trunking arrangement only six groups are necessary. The tandem trunking plan has the advantage that the trunk groups are comparatively large and therefore can be used more efficiently. It is obvious that the advantages of tandem trunking become very marked as the number of offices to be interconnected increases.

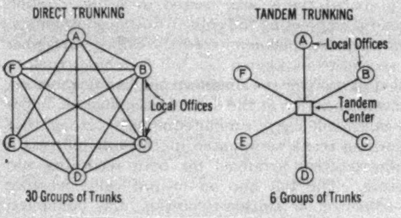
DIRECT TRUNKING
A
B
C
D
E
F
Local Offices
30 Groups of Trunks
TANDEM TRUNKING
A
Local Offices
B
Tandem Center
C
D
E
F
6 Groups of Trunks

FIG. 1—TRUNKING PLANS

A great many tandem systems are in operation today where the switching at the tandem office is done manually. There are a few installations where a moderate amount of tandem switching is done automatically. The first tandem trunking system to employ, on a large scale, apparatus for switching which is under the control of dials located at the various operators' positions tributary to the tandem office, was recently installed at Los Angeles to handle the short-haul toll traffic within a radius of approximately 40 mi. This system is known as a dial tandem system.

It is the purpose of this paper to describe the Los Angeles dial tandem system. A brief description is first given of the telephone area of southern California and of the various methods which existed for completing short-haul toll calls, and is followed by a discussion of some of the considerations which led to the adoption of the particular type of tandem system in question. A detailed description is then given of the equipment employed at the tandem center and at the outlying points, together with a method of operation.

It should not be inferred that a system similar to the one installed in Los Angeles should necessarily be regarded as suitable for other large cities, as there were certain conditions in this area, described later on, which made this type of installation particularly desirable.

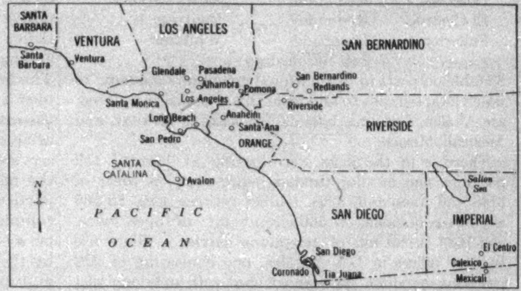
SANTA BARBARA
Santa Barbara
VENTURA
Ventura
LOS ANGELES
Glendale
Pasadena
Alhambra
Pomona
Los Angeles
Santa Monica
Long Beach
San Pedro
Anaheim
Santa Ana
ORANGE
SAN BERNARDINO
San Bernardino
Redlands
Riverside
RIVERSIDE
SANTA CATALINA
Avalon
N
PACIFIC OCEAN
Salton Sea
SAN DIEGO
IMPERIAL
El Centro
San Diego
Coronado
Tia Juana
Calexico
Mexicali

FIG. 2

### THE HANDLING OF SHORT-HAUL TOLL TRAFFIC IN THE AREA OF SOUTHERN CALIFORNIA PRIOR TO THE INSTALLATION OF THE DIAL TANDEM SYSTEM

The portion of the area in southern California in which short-haul toll calls are handled is approximately 300 mi. in length, along the Pacific Coast, varying in width from 5 to 100 mi., limited by ocean, mountainous contour and desert stretches, extending from the northern Santa Barbara County line to the southern international boundary. This area of approximately 24,000 sq. mi. is shown in Fig. 2 and consists of all or parts of the following California counties:

Santa Barbara
Ventura
Los Angeles
Orange
San Diego
San Bernardino
Riverside
Imperial

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[1] Southern California Telephone Co., 940 S. Olive St., Los Angeles, Cal.

[2] American Telephone & Telegraph Co., 195 Broadway, New York, N. Y.

*Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., September 13-16, 1927.*

These eight counties increased in population from 1,347,000 in 1920 to 2,412,000 in 1927, while the city of Los Angeles, alone, nearly doubled its population in the same seven years, from 612,000 in 1920 to 1,210,000 in 1927.

There are 145 telephone exchanges in the area varying in size from less than 10 to more than 325,000 stations. The type of local equipment and number of offices in these exchanges are:

42 Magneto manual offices
20 Small common battery offices
68 Large common battery offices
57 Dial system (step-by-step) offices
9 Semi-automatic offices (machine switching equipment controlled manually by means of operators).

In addition to, and separate from, the local, there are one or more toll boards located at the following places:

Alhambra
Anaheim
Corona
Covina
Downey
El Centro
Fullerton
Long Beach
Los Angeles
Pomona
Oxnard
Redlands
Redondo
Riverside
San Bernardino
San Diego
San Pedro
Santa Ana
Santa Barbara
Santa Monica
Ventura
Whittier

Notable outposts in our national telephone system, to which local toll calls to and from this area are completed, are Avalon, Catalina Island; Tia Juana, Mexico; and Mexicali, Mexico.

There is in the area, terminating at manual toll positions and at dial tandem equipment, a total of 3148 toll lines and 3294 trunks representing 52,866 circuit mi. of cable, 27,950 circuit mi. of open wire, and 1633 circuit mi. of telephone carrier. There are two toll offices in Los Angeles, one consisting of 222 positions, handling both short-haul toll and long distance calls, and a smaller office consisting of 96 positions, handling short-haul toll calls, exclusively.

Previous to 1919, short-haul toll calls in southern California were handled via toll switchboards with the exception of those between Los Angeles, Glendale, and Pasadena. The latter calls were handled either by direct trunks or by tandem trunks. Following this, some dial equipment was made available in Los Angeles, Santa Monica, and Long Beach, which permitted direct calling from the Santa Monica and Long Beach toll boards to Los Angeles dial stations. Certain Los Angeles toll board positions were also arranged for direct calling of all Santa Monica stations. In 1924, three Los Angeles toll board positions were arranged for straightforward tandem trunking for handling a portion of the short-haul toll calls from Los Angeles to Alhambra, Inglewood, Long Beach, Montebello, San Pedro, and Wilmington. In the same year it was necessary to make rather extensive provision of toll switchboard equipment to take care of the large amount of tributary toll traffic recorded in Los Angeles from Alhambra, Arcadia, Burbank, Compton, Covina, Cresenta, Downey, El Monte, El Segundo, Gardena, Hawthorne, Hynes, Inglewood, Lankershim, Monrovia, Montebello, Owensmouth, Redondo, San Fernando, Sierra Madre, Sunland, and Torrance.

It is apparent from the foregoing that a considerable number of channels existed for the handling and the completion of short-haul calls summarized as follows:

1. Calls recorded at toll boards via:
    a. Toll board and ringdown toll lines,
    b. Toll board and limited toll line dialing arrangements,
    c. Tributary recording board and toll lines.
2. Calls recorded at local boards:
    a. Direct trunks,
    b. Local tandem trunks,
    c. Straightforward tandem trunks and toll lines.

*1. Calls Recorded at Toll Board.*

a. Toll Board and Ringdown Toll Lines.

On originating person-to-person calls the subscriber's line was connected by the local operator first answering to a trunk terminating in the toll offices at segregated positions for recording the subscriber's call. The toll ticket prepared there, was passed to a line position arranged for completing toll calls to outlying exchanges. The line operator then connected the calling subscriber over a special trunk known as a toll switching trunk to the called party over the ringdown toll line terminating at an inward position at the distant exchange. Number service calls made use of similar equipment, except that the recording trunk terminated in the toll office at a particular position arranged for both recording and completing. The toll line on inward calls, whether person-to-person or station-to-station, was connected by the inward toll operator directly to the subscriber's multiple or over a toll switching trunk, to the called station.

b. Toll Board and Limited Toll Line Dialing Arrangements.

Toll calls completed by the limited dialing arrangements were identically handled, and required equipment similar to that described in the preceding paragraph, except that the toll line dialing equipment permitted the operator at the originating end to dial and obtain the called station at the distant end without passing through the inward toll board.

c. Tributary Recording Board and Toll Lines.

The toll calls from nearby outlying points that were handled at tributary recording boards, terminated on toll line equipment at the toll center on positions arranged for recording and completing. The toll line was there connected over a toll switching trunk to the called station, or if the call was to another exchange the line was connected to another toll line terminating at an inward position at the distant exchange.

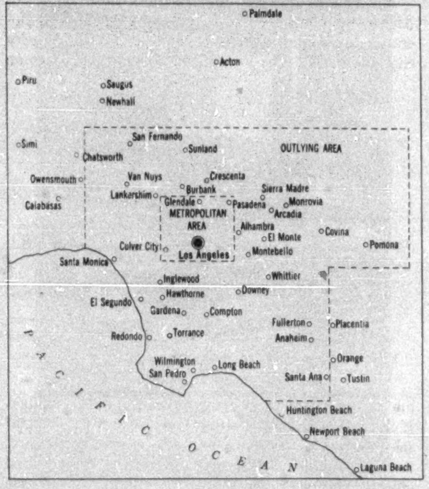
*2. Calls Recorded at Local Boards.*

a. Direct Trunks.

On an originating call completed over direct trunks, the subscriber's line was connected by the local operator first answering to interoffice trunk equipment terminating at a "B" position at the called office, and there was connected directly to the multiple of the called station.

b. Local Tandem Trunks.

On a call completed via the local tandem board the subscriber's line was connected by the local operator to trunk equipment terminating in the tandem office. This tandem trunk was then connected to interoffice trunk equipment terminating at a "B" position at the called office, and there was connected directly to the multiple of the called station. If the called station was in a dial office, the calling subscriber's line was connected by the local operator to dial trunk equipment terminating on incoming selectors in a dial office in the called exchange and there through the local trunk to the particular dial office.



Palmdale
Acton
Piru
Saugus
Newhall
San Fernando
Simi
Chatsworth
Sunland
OUTLYING AREA
Owensmouth
Van Nuys
Crescenta
Lankershim
Burbank
Sierra Madre
Calabasas
Glendale
Pasadena
Monrovia
METROPOLITAN AREA
Arcadia
Alhambra
Covina
El Monte
Culver City
Pomona
Santa Monica
Los Angeles
Montebello
Inglewood
Whittier
Hawthorne
Downey
El Segundo
Gardena
Compton
Fullerton
Placentia
Redondo
Torrance
Anaheim
Wilmington
Orange
San Pedro
Long Beach
Santa Ana
Tustin
Huntington Beach
Newport Beach
Laguna Beach
PACIFIC OCEAN

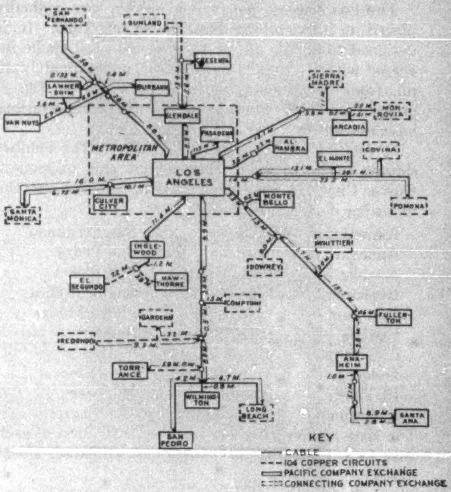
FIG. 3

c. Straightforward Tandem Trunks and Toll Lines.

In the straightforward trunking the information necessary for completing the call is passed to the distant operator over the same conductors used for establishing the connection. On an originating call completed via the straightforward tandem trunk board the subscriber's line was connected by the local operator to the straightforward trunk equipment terminating at a position in the Los Angeles toll office. This trunk was then connected to a ringdown toll line terminating at an inward toll position at the called office, and there was connected to the called station.

## CONSIDERATION WHICH LED TO THE INSTALLATION OF THE DIAL TANDEM SYSTEM

The abnormal demands for telephone service between cities and communities have more than kept pace with the growth in population. The facilities at times have been taxed to the limit and a few years ago it became evident that new methods of handling the short-haul toll traffic must be devised. The toll board method is adequate for long distance toll traffic, but a faster method was required for moving the unprecedented increase in short-haul traffic.



SAN FERNANDO
SUNLAND
CRESENTA
LANKERSHIM
BURBANK
VAN NUYS
GLENDALE
PASADENA
SIERRA MADRE
MONROVIA
ARCADIA
METROPOLITAN AREA
ALHAMBRA
EL MONTE
COVINA
LOS ANGELES
SANTA MONICA
CULVER CITY
MONTEBELLO
POMONA
INGLEWOOD
WHITTIER
DOWNEY
EL SEGUNDO
HAWTHORNE
COMPTON
GARDENA
REDONDO
FULLERTON
ANAHEIM
TORRANCE
WILMINGTON
LONG BEACH
SAN PEDRO
SANTA ANA
16.0 M.
6.75 M.
10.1 M.
11.4 M.
1.2 M.
1.5 M.
9.3 M.
4.2 M.
4.7 M.
0.8 M.
15.7 M.
13.1 M.
29.7 M.
33.2 M.
8.9 M.
1.0 M.
KEY
CABLE
104 COPPER CIRCUITS
PACIFIC COMPANY EXCHANGE
CONNECTING COMPANY EXCHANGE

FIG. 4

The requirements for a more rapid and adequate method for handling the short-haul toll traffic have caused the telephone company to focus its efforts on furnishing short-haul toll service comparable to local service, and in 1923 a study was made of the application of tandem systems for handling the station-to-station traffic around Los Angeles. Step-by-step tandem and straightforward manual tandem systems were studied, both proving to be more economical and faster than the toll board method, the former being more economical than the latter. Decision to proceed with the Los Angeles tandem system project was made as soon as the results of the study were determined; and the engineering work for specific installations was started immediately.

In 1924, switchboard position equipment was placed in service in various Los Angeles central offices to care for the necessary manual services for dial stations which provided a practical means for handling short-haul toll calls originating from dial stations. In the same year equipment was installed in all manual offices in order that dial stations could complete calls to manual stations in the same manner as calls to dial stations. This equipment is known as call indicator equipment and employs decimal switches and a bank of numbered lamps to record and display before an operator the number of the desired station. The operating features that these manual service positions and call indicator equipment provided, materially aided in reaching the decision to adopt the dial tandem system.

The Los Angeles dial tandem system was gradually placed in service, starting March 30, 1926. It is designed to handle all of the short-haul toll traffic included within a maximum radius of approximately 40 mi. from the tandem center as indicated in Fig. 3, except that which transmission and other considerations have prevented.

It was initially arranged to handle all the number service traffic between metropolitan area exchanges, Culver City, Los Angeles, Pasadena, Glendale, and the following outlying exchanges:

Alhambra
Anaheim
Arcadia
Burbank
Compton
Covina
Crescenta
Downey
El Monte
El Segundo
Fullerton
Gardena
Hawthorne
Inglewood
Lankershim
Long Beach
Monrovia
Montebello
Pomona
Redondo
San Fernando
San Pedro
Santa Ana
Santa Monica
Sierra Madre
Sunland
Torrance
Van Nuys
Whittier
Wilmington

The sizes of these areas in stations at the first of each year from 1925 to 1929, actual and estimated, are as follows:

| Area | Actual | | | Estimated | |
|---|---|---|---|---|---|
| | 1925 | 1926 | 1927 | 1928 | 1929 |
| | Stations | | | | |
| Metropolitan area: | | | | | |
| Four Exchanges | 293,577 | 318,440 | 352,634 | 388,235 | 419,585 |
| Outlying Area: | | | | | |
| Pacific Co. Exchanges | 23,803 | 27,435 | 31,646 | 37,645 | 42,620 |
| Connecting Co. Exchanges | 51,206 | 55,315 | 62,646 | 70,635 | 79,120 |
| Total | 368,586 | 401,190 | 446,926 | 496,515 | 541,325 |

Fig. 4 indicates the routes and miles of cable and open-wire circuits between exchanges.

In June, 1927, the system was expanded to handle number service between exchanges within the metropolitan area, and in addition, to handle about 95 per cent of the number service between exchanges in the outlying area.

Under present conditions, the longest through connection practicable to establish over the tandem system is 55.7 mi. from office to office.

### DESCRIPTION OF THE TANDEM SYSTEM

In general, the tandem system provides for a number of tandem trunks from the various offices in the tandem area terminating on first selectors of the step-by-step type located at the tandem center. Each level of the first selectors is wired to a group of second selectors on which are terminated completing trunks to the various offices served by the system. It will be noted that the use of first and second selectors will theoretically permit of reaching 100 different points, although practically this is somewhat limited because the first and zero levels of the first selectors are reserved for testing and special calls. As the system grows, third selectors can be introduced which will provide sufficient codes to care for the ultimate requirements. Two groups of first and second selectors are provided, one to handle calls from the outlying points to subscribers in Los Angeles, the other for calls from Los Angeles to subscribers in the outlying offices.

A subscriber in an outlying office desiring a Los Angeles number, see Fig. 5, will pass to his local operator the desired number as listed in the Los Angeles city directory. The local operator will then select an idle trunk to the tandem center and dial the number. If the call is to a dial system office, the first and second selectors at the tandem point will respond to the first two digits pulled by the operator to select the desired office. The remaining four or five digits, as the case may be, will be repeated on through the selectors and connectors at the terminating office to reach the proper called subscriber's line. If the called station is busy, a busy signal will be given to the originating operator. If the station is idle, the subscriber's bell will be rung automatically and upon the answer of the called party the supervisory cord lamp at the originating position will be extinguished as an indication to her that the called station has answered. The operation of the supervisory lamp by the called subscriber's switch hook provides the originating operator with complete supervision and a visual means for timing the call. After the completion of conversation, the calling and called parties will restore the receivers to the hooks, thereby causing the supervisory lamps on both cords to be lighted. The originating operator will then complete the timing, remove the answering cord from the

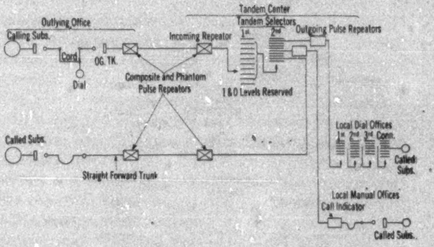


FIG. 5—EQUIPMENT ARRANGEMENT, SCHEMATIC DIAGRAM

subscriber's jack and the calling cord from the trunk to the tandem system which will cause the automatic release of all switches involved in setting up the connection. If the call is to a manual office, see Fig. 5, the connection will be established in exactly the same way except that the desired number will be displayed on one of the call indicator positions in the terminating manual office. The call indicator operator will complete the call in the same manner as she would a local call. The supervision obtained by the originating operator is the same as that described above for a call to a dial system subscriber. On calls from a manual office in Los Angeles to one of the outlying points, the functions performed by the subscriber and the local operator will be generally the same as that described above. On calls from a Los Angeles dial system office to an outlying office, the subscriber will first dial zero to reach his local operator after which the call will proceed in the same manner as described above for a call originating in a manual office. If the outlying point is a dial system office, the call will be completed in the same manner as described for a call from an outlying office to a dial system office in Los Angeles. If the call is for a manual outlying office, however, it will be completed by a straightforward operation; that is, the operator in Los Angeles will first dial the proper code to select a trunk to the desired outlying office. As soon as the trunk is seized, a signal will be displayed on the trunk before an incoming position. The incoming operator at the outlying office, upon answering the call, will automatically place a momentary tone on the connection which will indicate to the first operator that the incoming operator is ready to receive the desired number. The incoming operator, upon receiving the number, will complete the call to the desired subscriber by selecting the proper line jack in the manual switchboard multiple. As in the description of previous calls, the local operator in this case will also have complete supervision over both the calling and called subscribers.

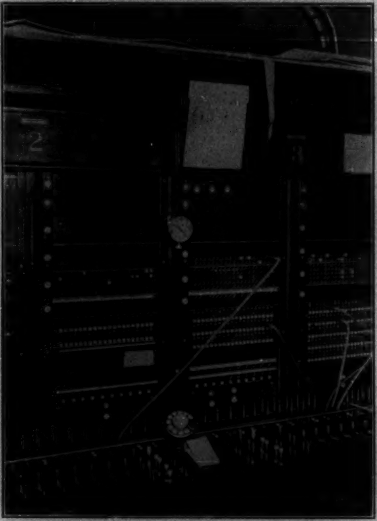


Fig. 6

Fig. 7

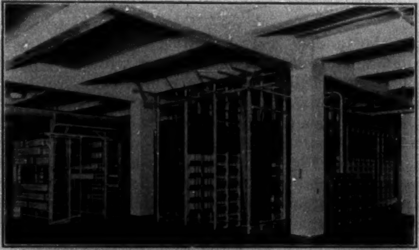


Fig. 8

The equipment required at an outlying office to provide the above described operating features consists in providing a sufficient number of tandem and completing trunks with their associated terminal equipment to handle the peak load of the traffic. The operator's cord circuits are modified so that her position dial can be associated with any cord; or in cases where the volume of traffic is relatively small, a cheaper arrangement, consisting of the provision of a dial cord, would be installed. It would be well to mention here that no equipment of this nature was required for the Los Angeles manual offices. These switchboards had already been modified for dialing and for call indicator operation in order to provide a suitable method for completing calls to and from dial system offices in the local metropolitan exchange area. If these modifications had not been made, the economies of the machine switching in preference to manual straightforward tandem operation might be questionable. Figs. 6 and 7 show the local operator's switchboard equipment and the tandem relay repeating equipment for seven outgoing and nine incoming phantomed trunks for the Hawthorne, California, office, which is typical of the outlying manual offices served by the tandem.

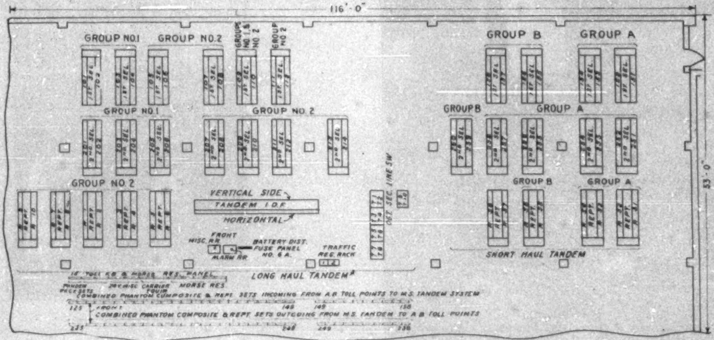

116'-0"
GROUP NO.1
GROUP NO.2
GROUPS NO.1 & NO.2
GROUP NO.2
1ST SEL.
GROUP NO.1
GROUP NO.2
2ND SEL.
GROUP NO.2
REPT.
VERTICAL SIDE
TANDEM I.D.F.
HORIZONTAL
FRONT
MISC. RR
ALARM RR
BATTERY DIST. FUSE PANEL NO. 6 A.
TRAFFIC REG. RACK
OGT. SEC. LINE SW
LONG HAUL TANDEM
TANDEM PACK SETS
24V MISC
CARRIER EQUIP.
MORSE RES.
COMBINED PHANTOM COMPOSITE & REPT. SETS INCOMING FROM A.B. TOLL POINTS TO M.S. TANDEM SYSTEM
125
148
149
156
FRONT
COMBINED PHANTOM COMPOSITE & REPT. SETS OUTGOING FROM M.S. TANDEM TO A.B. TOLL POINTS
225
248
249
256
GROUP B
GROUP A
GROUP B
GROUP A
GROUP B
GROUP A
SHORT HAUL TANDEM
53'-0"

Fig. 9

Fig. 8 gives a general view of the tandem equipment at Los Angeles. The floor plan layout of the equipment is shown in Fig. 9. On the left-hand side are the first and second selectors, pulse repeaters, distributing frame and outgoing secondary switches for completing calls to and from the more distant points; on the right-hand side the first and second selectors and pulse repeaters for completing calls to and from the nearby points are served by the tandem system. The first group, as noted on the sketch, is designated for convenience as the long-haul system and the second group as the short-haul system. These terms are merely equipment group designations and it should not be inferred that the two groups are provided for handling two types of traffic. A total of 2500 trunks terminates at the tandem office and 4000 selectors are required to do the switching.

The group of switches designated short-haul system performs the same functions as the group designated long-haul system except that it provides for the completion of calls to and from certain of the neighboring points to Los Angeles. The purpose of providing the so-called short-haul group is to permit of the use of small gage conductors on trunks which carry a relatively high volume of traffic between Los Angeles and outlying offices within approximately a 10-mi. radius. As an illustration of the economy of this arrangement, it would be necessary, if all calls to Pasadena were completed through a single group of tandem switches, to provide approximately 150 16-gage conductors in order that calls from Santa Ana, for example, would receive satisfactory transmission, although such calls are relatively few as compared with the total volume of traffic to Pasadena. By providing a separate group of selectors, known as the short-haul system, 20 conductors of 16 gage would be required on the long-haul system, whereas the remaining 130 trunks to Pasadena from the selectors of the short-haul system are of 19 gage and entirely satisfactory for the transmission requirements of the calls which it handles. The annual charges on 16-gage conductors per mile are approximately two times those for 19 gage.

A description of the selectors employed in the tandem system at Los Angeles is not required as they are of the well-known standard step-by-step type and are wired together in accordance with standard practises except that a cross-connecting frame is provided between selectors in order that the system will lend itself readily to expansion or other necessary rearrangement which may be brought about by future changes in traffic conditions.

The power for operating the various selectors, pulse repeaters, and out-trunk secondary switches is obtained from the power plant of a standard step-by-step dial system central office located in the same building as the tandem equipment. At a number of the outlying offices it was necessary to add cells to the battery in order to raise the voltage to 48, which is required for the proper operation of the circuits.

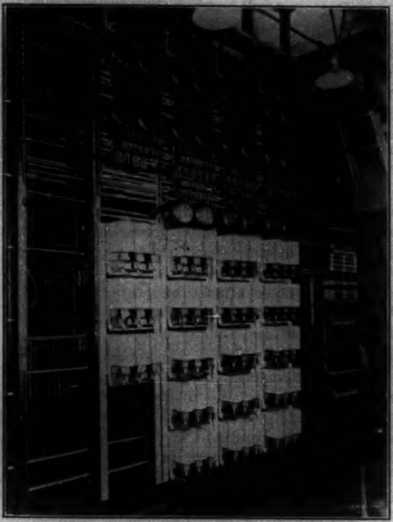


Fig. 10

The pulse repeaters which are used on both the incoming and outgoing trunks from the tandem and outlying offices to repeat dial impulses from one section of the circuit to another are new both with respect to circuits and to the association of various pieces of apparatus required in circuits. Fig. 10 shows the typical layout of a pulse repeater frame for phantom trunks. The relays of the pulse repeater are mounted on a removable base and covered as a protection against dust in the same manner as standard equipment. The associated composite and repeating coils are shown mounted directly above the repeater relay equipment. It is the usual practise in engineering toll telephone equipment to mount the composite and repeating coils together with their associated condensers on separate frames and wire this apparatus to test jacks on the toll testboard. Such an arrangement will provide a rapid means for replacing defective apparatus which may have rendered an expensive toll line inoperative. It was decided in the engineering of this installation to forego some of this flexibility since the toll lines involved did not exceed approximately 40 mi. It was, therefore, practical to associate the composite and repeating coils on the same frames as the relays, an arrangement which effects considerable economy in floor space, mounting racks, and cabling, and also facilitates maintenance. The results of the operation of the tandem system with respect to maintenance, apparently justify our engineering decision in this respect.

In cases where large groups of trunks were required to handle traffic, such as between Long Beach and Los Angeles, considerable economy was effected by the use of outgoing trunk secondary switches. These switches perform the same function as the standard primary and secondary line switch arrangement employed in step-by-step dial system offices, the theory of which has been described in previous papers. Of course, in the case of the tandem system the economies are somewhat more marked, due to the fact that the trunks involved are considerably more expensive than the trunks which are saved by the use of secondary line switches in local step-by-step office practises.

Where phantom trunks are not used, the pulse repeaters are the same as those employed between local Los Angeles offices.

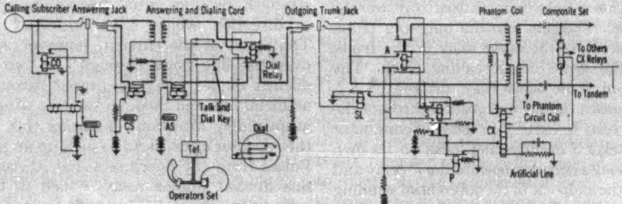


Fig. 11—Outlying Office Simplified Circuits

Referring now to the operating features of the principal circuits involved in completing a call through the tandem system, see Fig. 11 which illustrates a typical circuit at an outlying manual office used in a call to a Los Angeles dial system subscriber. Particular attention will be given to a description of the novel dialing and signaling arrangement for phantom trunks and to the pulse correcting device of the incoming pulse repeater circuit.

When a calling subscriber in an outlying office lifts his receiver to originate a call, a circuit is closed from battery through the line relay on the contacts of the station switchhook. The resultant operation of the line relay closes a circuit to light the line lamp appearing before the operator who answers the call by inserting a plug of an answering cord into the subscriber's jack associated with the lighted line lamp. This closes a circuit by way of the sleeve of the answering cord to the cutoff relay in the line circuit, causing it to operate and disconnect the line relay from the subscriber's line, opening the lamp circuit, and extinguishing the line lamp. Battery is fed from the cord circuit repeating coil to the subscriber's set to energize his transmitter, and the calling supervisory lamp is under the control of the station switchhook.

The operator then obtains the desired number from the calling subscriber and if the number is in a local dial system office in Los Angeles she will select an idle trunk to the Los Angeles tandem office and insert therein the other end of the cord which she has used to answer the calling subscriber. Plugging into the outgoing trunk jack closes the circuit of the sleeve relay in the trunk to battery on the sleeve of the calling cord. The resultant operation of the sleeve relay, designated $S\,L$ on the sketch, closes a circuit from ground through the winding of the $S$ relay to battery on the ring conductor of the trunk. Relay $S$ operates and locks on its own front contact, closing a circuit to operate the $P$ relay and apply battery to the midpoint of the differential winding of the $C\,X$ relay. Relay $S$ also applies battery to the winding of the $A$ relay which does not operate at this time.

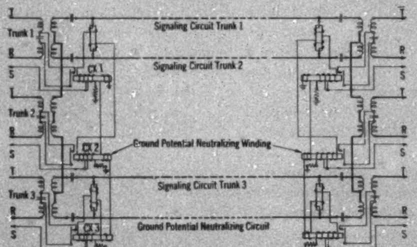

T
Trunk 1
R
S
Signaling Circuit Trunk 1
Signaling Circuit Trunk 2
CX 1
Trunk 2
CX 2
Ground Potential Neutralizing Winding
Trunk 3
Signaling Circuit Trunk 3
CX 3
Ground Potential Neutralizing Circuit

FIG. 12—PHANTOM TRUNK GROUP

Composite sets and phantom coils. Relays compensated for ground potential difference, simplified circuit.

The operator in dialing pulls the dial off normal, closing its off-normal contacts and operating the dial relay to associate the dial with the calling cord. The operation of this relay disconnects the repeating coil from that end of the cord and connects ground through the pulsing contacts of the dial to the tip conductor and ground through the off-normal contacts to the ring conductor of the cord. This latter application provides an operating ground for the $A$ relay in the trunk, whose principal function is to connect the $P$ relay to the tip conductor so as to prepare it to receive the pulses from the dial. The $P$ relay repeats the pulses to a relay, corresponding to the $C\,X$ relay of the trunk, in the incoming repeater at the tandem center, at the same time not affecting the $C\,X$ relay in the trunk, which is used to receive a signal upon the answer of the called party and so extinguish the lighted supervisory lamp in the calling cord.

This two-way signaling feature, *i. e.*, pulsing in one direction and supervising in the other, over a single wire, is accomplished by an application to telephone signaling circuits of the familiar duplex principle of telegraphy. This application makes possible the use of phantomed trunks from the outlying points to the tandem center with accompanying economies in outside plant.

These trunks, as shown in Fig. 12, are provided with phantom coils and simplified composite sets, through which the four metallic leads of the phantom group are brought out to duplex relays. All of this apparatus is interposed on these trunks between the regular out-dialing trunks, already described, and the incoming pulse repeaters at the tandem center.

Referring to the diagram, the action of an out-trunk circuit when picked up by an operator is to furnish battery instead of ground to the lead designated $S$ on the particular channel selected. The resultant battery flow passes to the midpoint of the differential winding of the duplex relay and there divides in equal parts, one part passing by way of one-half of the differential winding over the line to the distant relay at the tandem center and the other part passing through the other winding and through an artificial network of electrical characteristics similar to the line attached to the other winding. These two current flows, being equal in strength, produce equal magnetomotive forces opposite in direction which have no effect upon the relay. That part of the current, however, which has passed over the line flows through the two windings of the distant duplex relay to ground through its associated artificial line and through the two windings of the relay in an aiding direction, operating this relay to actuate the repeater circuit and so pick up an incoming selector. Pulses from the operator's dial, therefore, will control this distant duplex relay, which in turn sets up the connection through the tandem system in the usual way.

On the answer of the called party, the incoming pulse repeater furnishes battery instead of ground to the lead designated $S$, which flows in opposite directions through the duplex relay windings, one part through the artificial line and the other over the line, through the two windings of the duplex relay at the outlying point. The operation of this relay retires the operator's supervisory lamp in the calling cord, indicating to her that the called party has answered.

At the completion of conversation, the hang-up of the called station causes the incoming selector to remove battery from the duplex circuit, releasing the *C X* relay which lights the supervisory lamp associated with the calling cord as a disconnect signal. The disconnect of the operator removes the battery from the lead *S*, thereby releasing the distant duplex relay, which in turn releases the switch train.

A similar operation takes place when the phantom channel, designated "Trunk 2," in Fig. 12, is selected by an operator. The signaling, however, is done over the second wire of the first metallic pair. For the other side circuit, designated "Trunk 3," the signaling is done over one of the wires of the other metallic pair. This, it will be observed, utilizes but three wires of the four in the phantom group, allowing the use of the fourth to overcome any effect on the signaling relays which might be occasioned by current flow due to adverse ground potentials. This is accomplished by adding to each of the duplex relays a third winding, all connected in series by means of the fourth lead. Any ground potential difference between the two ends of the circuit which might cause current to flow through the differential windings of the duplex relays will be neutralized in effect by a similar current flowing through the compensating windings over the fourth wire.

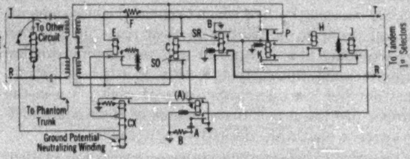


FIG. 13—INCOMING PULSE REPEATER

With pulse corrector simplified circuit

The incoming pulse repeaters into which the duplex-composite circuits work have embodied in them a means for correcting for the distortion of dial pulses due to line characteristics. The use of this feature in the incoming repeaters makes it feasible to provide reliable service over longer trunks than has heretofore been practicable and so embrace in the system as many towns within the wide range of the tandem area as are economically warranted.

When the trunk is selected by an operator at an outlying point, the *C X* relay of the incoming repeater at the tandem center shown in Fig. 13 is energized, as has been explained. This relay operates the *A* relay of the incoming repeater directly on its front contact, closing a circuit to operate a "slow operate" relay *C* and a "slow release" relay *B* in series. The latter relay closes a circuit to operate the *K* relay which locks, operated on its own front contact through a back contact of the *J* relay. The *K* relay also closes a circuit to operate the *H* relay which opens the original operating circuit of the *K* relay and closes on the contacts designated *P*, a bridge across the inside terminals of the repeating coil consisting of resistance *F* and relay *E* in series.

Current from the first selector of the tandem train flows through this bridge operating the *A* relay of the first selector in the usual way. Relay *E* is not affected by this current flow since it is polarized to operate on a current in the reverse direction.

At the first pulse from the operator's dial at the outlying point, the circuit operating the *C X* relay is opened, causing the release of that relay. The *A* relay in turn is released, opening the circuit through the *C* and *B* relays. The former releases, and being slow to operate, remains released during the train of pulses following, while the latter, being slow to release, remains operated during this time. On its other back contact, the relay *A* grounds the condenser *A* through the resistance *B*.

On the opening of the circuit at the first pulse, nothing occurs in the repeater to affect the condition of the associated first selector. On the closure of the circuit at the end of the first pulse, a pulse of measured length is sent to operate the first selector as follows:

The operation of the *C X* relay closes the circuit to the *A* relay which connects the discharged condenser *A* to battery through the winding of relay *J*. On the short surge of charging current the relay *J* momentarily operates, opening the locking circuit of the *K* relay, causing it to release, and open the contacts designated *P* to start the first pulse to the selector. The release of the *K* relay also opens the circuit to the winding of the *H* relay which, when released, establishes the original operating circuit of the *K* relay, which operates to close the *P* contacts completing the pulse and to lock through the now restored back contact of the *J* relay.

The length of the pulse to the first selector is determined by the release and operate time of the *H* and *K* relays, respectively, thus correcting for any distortion of dial pulses due to line characteristic.

Succeeding pulses of the first digit and following digits are repeated in like manner to the selectors of the tandem train of switches, and through an outgoing trunk repeater to the switch train of the local office, to select in the manner well known in step-by-step practise, the terminal of the called line.

Upon the answer of the called subscriber, the battery flow from the tandem switch train to the incoming repeater is reversed, operating the polarized relay *E*. The midpoint of the differential winding of the *C X* relay is thereby changed from ground to battery, causing, as previously outlined, the operation of the *C X* relay in the outgoing trunk at the outlying office and the subsequent extinguishing of the calling supervisory lamp.

At the completion of conversation the current flow through the *E* relay again reverses, causing the release of the relay and lighting of the distant supervisory lamp as a disconnect signal. The disconnection by the operator releases the *C X* and *A* relays, opening the circuit to release the *B* and *K* relays. The opening of contact *P* of the *K* relay restores the switches of the tandem train.

Where the trunks outgoing from the tandem office terminate in local manual offices equipped with call indicator completing positions, a pulse repeater is provided to repeat the decimal pulses directly to the call indicator display apparatus. This apparatus is substantially the same as that in use in panel dial system offices which has been described in early papers on the panel system[2].

Trunks outgoing to manual offices not equipped with call indicator are operated by what is known as the straightforward trunking method. This method embraces most of the offices in the outlying towns which connect to the tandem system, and a simplified diagram of one of the types of trunk circuits is shown on Fig. 14.

When the trunk is selected at the tandem point, the outgoing repeater sends battery over one of the wires of the phantom trunk group, in a manner similar to that already described for the outgoing trunks, to cause the relay *C X* to operate, lighting the guard lamp through a chain of relays to appraise the operator of a waiting incoming call. The operator answers by operating the talking key on the completing trunk, bringing into play apparatus in her telephone circuit which sends a momentary tone to the calling operator, to advise her that the completing operator is ready to receive the call. She then plugs the completing cord into the multiple jack of the line desired.

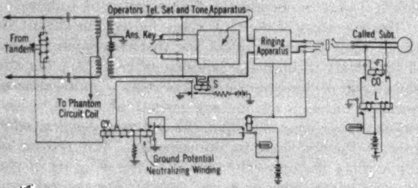


Fig. 14—Complete Trunk, Simplified Circuit

The sleeve circuits of the cord and line are closed, operating the cut-off relay in the line to remove the associated line relay and setting in operation the machine ringing apparatus in the cord.

When the called subscriber answers, machine ringing is tripped and the circuit closed through to the repeating coil in the cord. Battery through the repeating coil flows over the line to energize the station transmitter and operates the series supervisory relay *S*. This relay in operating places battery on the midpoint of the differential winding of the *C X* relay, causing the *C X* relay in the outgoing repeater to operate, and by means of a reversing relay, reverse the battery flow through the tandem switch train to the incoming repeater. As already described, this results in retiring the calling supervisory lamp at the originating office.

At the completion of conversation the hang-up of the calling party lights the calling supervisory lamp as a disconnect signal and the called party's hang-up lights the other supervisory lamp. The disconnect of the originating operator releases the tandem switch train, in turn releasing the outgoing trunk and lighting the disconnect lamp through the back contact of the now restored *C X* relay at the completing position.

## Placing the Tandem System in Operation

With the introduction of the dial tandem service came many interesting problems. As in most cases where communities are joined together by new communication methods, the various interests and general viewpoints of those concerned present an interesting and difficult problem to solve on a mutually satisfactory and equitable basis. The area includes 12 connecting companies which were using five different makes of equipment. The two larger of these included one exchange of 28,000 stations and another of more than 13,000 stations, both of which originated a large amount of toll traffic in proportion to their size. In addition to providing new equipment and rearranging existing equipment at the outlying points, it was necessary to instruct the local operating force at each place in the proper operation and maintenance of their equipment in order to obtain the desired service results.

In order to acquaint the operators with the tandem system, a number of bulletin cards with the names and codes of offices was prepared and placed on each position handling tandem calls. Information and instructions as to whether the tandem code together with the subscriber's number or only the code should be dialed in passing the order to the completing operator, also were included. The accompanying table shows one of these bulletins. Very little educational work was required in the training of the operators in Los Angeles as they were already accustomed to dialing. The straightforward completing feature of the tandem system was quite like the manual straightforward tandem system already in operation. Considerable training was done in the outlying offices, however, as many of the operators were not accustomed to dialing and in some cases were not familiar with the requirements in the proper handling of short-haul toll traffic. A brief description of the tandem method of operation was prepared for each outlying town, which was discussed with the supervisory officials who presented the problem to their forces. The questions and answers presented in these conferences resulted in a knowledge of the system as well as the details of the operators' work being known to the operating forces before service was started. In establishing the many routes which were made effective with the opening of the tandem system, it was essential that

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[2] Paper by Craft, Morehouse, and Charlesworth, A. I. E. E. Trans. Vol. XLII, 1923, p. 187.

| Complete by name or number | | | | Complete by number |
|---|---|---|---|---|
| Fire Department | FItzroy 3131 | Without charge | | Without charge |
| Emergency Hospital | FAber 1441 | Information | 113 | FAber 9000 to FAber 9999 |
| | | Repair Clerk | 114 | All Offices 0000 to 0009 |
| Receiving Hospital | | Wire Chief | 117 | |
| Police Department | MEtropolitan 6100 | U. S. Long Distance | 118 | |
| Sheriff's Office | TRinity 9111 | Pacific Long Distance | 110 | |
| | | Pacific Telegraph | FAber 9045 | |
| | | Telephone Company | FAber 9060 | |

NUMBER SERVICE INFORMATION

| Name | Abr. | Route-Code | Initial Rate | Name | Abr. | Route-Code | Initial Rate |
|---|---|---|---|---|---|---|---|
| Alhambra | Alh | I H-21 | 10c | Long Beach | L Bch | LH-52* | 20c |
| Anaheim | Anhm | LH-42 | 25c | Moneta | | LH-25-Gard | 10c |
| Arcadia | | A-B-T | 15c | Monrovia | Mon | A-B T | 15c |
| Brea | | 2 $ | | Montebello | Mont | LH-37 | 10c |
| Burbank | Brb | LH-32 | 10c | Newhall | | 2 $ | |
| Chino | | 2 $ | | Niagara | Nig | Stf (Col) | 10c |
| Claremont | Clmt | 2 $ | 25c | Orange | Org | 2 $ | |
| Colorado | Col | Stf | 10c | Owensmouth | Omth | A-B T | 20c |
| Compton | Comp | LH-30 | 10c | Placentia | Plac | 2 $ | |
| Covina | Cov | A-BT | 20c | Pomona | Pma | 2 $ | |
| Crescenta | Crsn | LH-46 | 10c | Redondo | Rdn | A-B T | 15c |
| Culver City | Clv | A-BT | 10c | | | | |
| Downey | Dny | 2 $ | | San Dimas | S Dms | 2 $ | |
| Duarte | | A-BT-Mon | 15c | San Fernando | S Fdo | A-B T | 20c |
| El Monte | El-Mt | LH-23 | 10c | San Gabriel | | LH-21 | 10c |
| El Segundo | El Sg | LH-24 | 15c | San Pedro | S P | LH-41 | 20c |
| Fair Oaks | Fo | Stf (Col) | 10c | Santa Ana | S Ana | LH-44 | 25c |
| Fullerton | Ful | LH-43 | 20c | Santa Monica | S Mon | LH-53* | 15c |
| Gardena | Gard | LH-25 | 10c | Sierra-Madre | S Mdr | A-B T | 15c |
| Garden Grove | | 2 $ | | Sterling | Stg | Stf (Col) | 10c |
| Glendale | Gln | C.C. | 10c | Sunland | | A-B T | 15c |
| Hawthorne | Hthn | LH-47 | 10c | Terrace | Ter | Stf (Col) | 10c |
| Huntington Bch | HtBch | 2 $ | | Torrance | Tnce | A-B T | 15c |
| Hynes | | 2 $ | | Tustun | | 2 $ | |
| Inglewood | Ingl | A-B T | 10c | Van Nuys | V Nys | LH-39 | 15c |
| Lankershim | Lank | LH-36 | 10c | Wakefield | Wak | Stf (Col) | 10c |
| La Verne | La V | 2 $ | | Whittier | Whtr | LH-54* | 15c |
| Lomita | Lta | 2 $ | | Wilmington | Wlmg | LH-45 | 20c |

*To these points the subscriber's number must be dialed in addition to the code

On Calls by Name to Offices Underlined in Red Advise the Calling Party that the Call Should be Given to U. S. L. D.

On Calls by Name to Offices in Red Advise the Calling Party that Particular Person Calls are not Accepted

On calls by name to offices in black connect the calling party with long distance

| | Computed Charges | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Initial rate | 5.1 to 6 min. | 6.1 to 7 min. | 7.1 to 8 min. | 8.1 to 9 min. | 9.1 to 10 min. | 10.1 to 11 min. | 11.1 to 12 min. | 12.1 to 13 min. | 13.1 to 14 min. | 14,1 to 15 min. | Overtime rate |
| 10c for 5 min. | 15c | 15c | 15c | 20c | 20c | 20c | 25c | 25c | 25c | | 5c for ea. 3 min. |
| 15c " 5 " | 20c | 20c | 25c | 25c | 30c | 30c | 35c | 35c | 40c | 40c | 5c " " 2 " |
| 20c " 5 " | 25c | 25c | 30c | 30c | 35c | 35c | 40c | 40c | 45c | 45c | 5c " " 2 " |
| 25c " 5 " | 30c | 35c | 40c | 45c | 50c | 55c | 60c | 65c | 70c | 75c | 5c " " 1 " |

means be provided so that customers might easily obtain telephone numbers in other exchanges and the necessary routines were established to accomplish this.

A series of tests of equipment was made at the outlying offices where limits were severe. These tests included dialing and signaling from minimum to maximum limits with respect to line leakage and line balance resistance, relay adjustments, and voltage variation. The amount of cross-talk and audible interference from dialing and signaling was determined. On open-wire routes, particular attention was directed to line leakage and balance of composite sets located at the cable junction. When placed in service, each cut-over operation was limited to trunks in one direction only and, as far as possible, but one office was brought in at a time. Thus, the change from the toll board to the dial tandem method was carried out in an orderly manner with the least possible confusion to and reaction on service. In some cases, a few trunks only were placed in operating condition several days before actual service was established over the route in order to give the operators preliminary training during their regular work. Maintenance routines and practises were issued sufficiently in advance of the cut-over so that practically no difficulties were experienced in equipment failures. Very close cooperation was necessary between the equipment and traffic engineers and the cut-over field forces of the Traffic and Plant Maintenance Departments. The schedule of cuts was thoroughly coordinated and the people who were finally charged with the responsibility of operating and maintaining the system were well trained.

It was originally planned to cut-over all the offices involved during May, 1926, and in addition, to introduce number service to other points within a 40-mi. radius of Los Angeles. With the completion of the installation at the tandem office in March, it was found possible to start service earlier to most of the offices handling a comparatively large volume of the traffic. A sequence cut, therefore, was planned which would permit the tandem system to carry the traffic gradually, avoiding any too abrupt change in operation or labor requirements in the various offices. The actual cut-over of the initial equipment comprised a period of nearly two months. Following this, other exchanges have been given the service from time to time, temporary equipment being replaced with permanent, so that there now remain only six points originally planned for the tandem system that are not actually receiving its full benefit. These exchanges are Arcadia, Covina, Pomona, Redondo, Sunland, and Torrance. The most recent cut-over of magnitude in this connection was in June, 1927, when Pasadena was changed from manual to dial operation. At this time a tandem center was established serving Pasadena exchange with direct connections to four Los Angeles offices and to the following outlying exchanges: Alhambra, Arcadia, Crescenta, Glendale, Monrovia, and Sierra Madre.

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## Discussion

### ADVANCE PLANNING OF THE TELEPHONE TOLL PLANT IN LONG-DISTANCE COMMUNICATION

(CHAMBERLIN)

### TANDEM SYSTEM OF HANDLING TOLL CALLS IN AND ABOUT LOS ANGELES

(JACOBSEN AND WHEELOCK)

DEL MONTE, CAL., SEPTEMBER 14, 1927

**M. R. Sullivan:** Speaking as a telephone traffic engineer, I should like to endorse what Mr. Chamberlin has said with respect to the traffic features involved in advance planning of telephone toll plants.

Traffic in the telephone industry takes the form of telephone calls or messages and since the plant is provided for the purpose of transmitting messages, the traffic features—the volume of traffic, the character of the traffic, the routing of the traffic, and the manner of handling of the traffic—are of controlling importance in the determination of the size and type and arrangement of the plant to be provided.

Mr. Chamberlin has outlined the important function of the commercial surveys in forecasting telephone developments with respect to growth in the number of telephones and their distribution by area, and by classes of telephone service.

Of equal importance are the forecasts of telephone calls per telephone. Telephone usage per telephone—particularly toll usage—does not remain constant year by year, but varies with business activities, and is subject to other influences, so that in the advance planning of the telephone toll plant it is necessary to give very careful study to the trend in the usage per telephone.

During the past few years, and especially during the last one or two years, there has been a marked trend upward in the toll usage per telephone. Many influences, no doubt, have played a part in this greater usage of the service. A feature of outstanding importance in this increase in toll usage lies, undoubtedly, in the results secured through various improvements which have been made in the toll service. For example, transmission within the last few years has been materially improved. It is easier to carry on intelligible conversation over the circuits, and that, of course, has had an effect upon the amount of toll business offered. In addition, the speed of handling the calls, and the convenience with which the call can be placed, has materially improved.

Up to a year or so ago, for a long-distance call, the calling party had to give details of the call to the long-distance operator, hang up the receiver, and later be called back when the connection was ready, or when a report on the call was obtained. This manner of handling a toll call required five or six minutes.

Today by giving the number desired to the long-distance operator, the chances are about nine to ten that the call will be completed immediately and without the necessity of even hanging up the receiver. The convenience of placing calls and the improved speed which this change has brought about has an effect in stimulating the number of toll calls offered.

Another recent change of considerable importance in the handling of toll calls is the proportion of calls handled by the "exchange operator." When I say exchange operator I refer to those completing connections from one telephone to another in the same exchange. The easiest way of placing a toll call is for the party calling simply to give the number of the desired call to the exchange operator, in the same manner as for a local connection. This method also produces the fastest service. For many years, large numbers of the toll calls have been handled by this method but of recent years there have been developments which greatly extended the range to which this most desirable of operating methods can be applied.

One of the developments is the improved tandem system of routing toll calls, which Mr. Wheelock has described. The result is that today a very much larger proportion of the toll calls is handled by this method. Take the exchange of Monterey; something like 48 per cent of all the toll calls originating at this exchange are handled by the exchange operator; whereas two or three years ago none of the toll calls was so handled. This improved method, therefore, has had application not only at the large metropolitan exchanges but also at the small exchanges.

I think it might be said that, like the automobile industry, the telephone toll business is constantly producing a bigger and better service; and in the advance planning of the toll plant, it is necessary to foresee the further improvements which will be made in the toll service and the effect these improvements will have on the volume of toll business offered and the size of the plant required.

**R. C. Barton:** Mr. Chamberlin's paper makes clear certain high lights of technic of the telephone business, and why universal and uniform telephone service is a natural objective.

As he has pointed out the value of the service to those who have it is increased by each addition to the system. Universal service, therefore, becomes a strong objective. He has indicated that the service must satisfy the party called as well as the calling party, so that service from the customer's viewpoint is demanded, and that calls for uniformity and standardization.

The paper brings out three important and distinctive characteristics of the telephone plant. One is that there is a very great multiplicity of lines and associated apparatus; another, that each line must be electrically smooth and stable in its operation; and the third, that the character of the telephone plant is continuously and rapidly changing.

In regard to this great multiplicity of lines exclusive use of the lines between parties is, to some extent, obviated in the toll-plant through the use of phantom circuits and carrier channels; however, Mr. Chamberlin's description of the San Francisco-Sacramento toll cable shows that multiplicity of lines is a strong characteristic of the telephone plant. This is more pronounced in the exchanges where the lines provided in one office district may be of the order of 100,000 and the conductor footage of the order of hundreds of millions.

Stability and smoothness are required in the electrical characteristics of the lines because of the complicated wave pattern which must be faithfully transmitted. The effect of rapid change may be appreciated by considering the condition produced when it becomes necessary to throw all the wires on a 50- or 60-wire toll line into cable.

These distinctive characteristics of the plant and of the service are largely responsible for the special engineering, construction and maintenance practises which are followed in the telephone art. One of the practises which receives very special emphasis has been made the key-note of Mr. Chamberlin's paper. It touches those activities which have to do with the study of the field of operations with respect to potential telephone development and the preparation of well matured plans, looking far to the future, to serve as a guide in the orderly placing of the plant.

Now the nature of the problem also requires another kind of advance preparation which takes the form of engineering, construction and maintenance handbooks. These are prepared to relieve the engineers of much of the work they would have if each job were designed from the ground up at the time it was being planned. These handbooks also insure the orderly placing of the plant in accordance with practises which have received nation-wide study and application.

It may be of interest to indicate something of the extremes to which it is desirable to go in such activities.

As one illustration, The Pacific System maintains a supply catalog which is available to all interested employees, and this catalog lists all materials, tools, and apparatus used in the conduct of their work. It is profusely illustrated and comprises about 500 letter-size pages. Among the items listed in this catalog are the handbooks previously mentioned. There are 75 of these devoted to the subject of construction methods alone, and some 100 supplementary leaflets affecting these. The construction methods handbooks cover such subjects as pole-line placing, underground conduit construction, guying, aerial-cable placing, etc. To the subject of aerial-cable placing alone, 120 handbook pages are devoted. These are well illustrated, and this book is typical of the others. Illustrative of the engineering handbooks is one on pole-line design. With this book, the engineer may quickly and easily determine the class of pole to select for any set of conditions, such as service value of the line, wire and cable load, temperature, wind and sleet conditions, span length, etc. Illustrative of the maintenance handbooks is one devoted to pole-line replacement and reinforcement inspection. This handbook prescribes the methods to be used in making inspections and includes tables of minimum ground-line circumference below which poles under the various conditions of load, service value, etc., are not permitted to go.

I should like to endorse Mr. Chamberlin's remarks regarding the value of cost-comparison studies in engineering, and the value to the student engineer of a fundamental knowledge of the procedure in such studies.

Making cost comparisons is a measurement process in which the principal unit is the dollar. One of the great physicists—Lord Kelvin, I believe—has written: "When you can measure what you are talking about, you know something about it; and when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind."

The rules of the mathematics employed when relating the various quantities developed in a measuring process require all quantities to be expressed in like units. For example, in a space measurement, units of length may arise as inches, feet, and yards, and require all to be expressed as feet by the application of suitable conversion factors. Likewise, in measurements where the dollar is the unit, it is required that before quantities of money may be properly compared, they must be operated upon by suitable conversion factors which will reduce all expenditures and investments such as first costs, present values, periodic payments, future recoveries, and the like, to a common time basis. The laws governing the set-up of the postulates and the facts in this sort of problem, and the method of solution, constitute the fundamentals of cost analysis, and it is these fundamentals which I agree with Mr. Chamberlin should be given some prominence during the college course. This is not done now.

**Bancroft Gherardi:** I was particularly interested in the remarks about inductive coordination, for, in the last five or six years, I have been the representative of the Bell system, working with R. F. Peck, the representative of the National Electric Light Association on the Joint Engineering Subcommittee, to solve our problems of inductive coordination; and before we had gone very far into that work, we came to the conclusion that 10 per cent of our problem was technical and 90 per cent was to bring about between the people on both sides of the question, a friendly and cooperative approach to that question.

It is evident that here, as in other parts of the United States, the problem is generally being approached cooperatively, and thus we are able to find mutually satisfactory solutions.

**N. B. Hinson:** Mr. Gherardi has called attention to the fact that there are certain classes of work that can hardly be classed as electrical engineering being done by the telephone companies. Mr. Chamberlin in his paper has emphasized this fact, and the same thing is true of the power system where there are certain elements of planning which are not electrical at all.

The telephone companies were the pioneers in the making of development surveys and population studies which could be used in advanced planning. A number of the power companies are falling in line with the same idea and finding population surveys in rapidly growing territory, like southern California, very useful, especially where yearly increases as high as 15 and 20 per cent occur.

**J. E. Heller:** (communicated after adjournment) Mr. Chamberlin has pointed out that the advance planning of telephone toll plant requires the coordinated effort of several departments, who, in turn, require specialists to solve the problems requiring their participation in the project.

As indicated in the paper, open-wire carrier-current systems and cable conductors may be used to provide long-distance communication circuits. The use of a given type of facility requires the determination of electrical as well as economic factors. After making allowance for the transmision losses of the trunking and local loop plant used at each terminal, it is electrically possible at the present time to talk with various facilities over the distances given below:

| Type of Facility | Mi. |
|---|---|
| 104 Open-wire | 5000 |
| 165 Open-wire | 6700 |
| 19-Gage 2-wire cable circuits | 700 |
| 16-Gage 2-wire cable circuits | 1200 |
| 19-Gage 4-wire cable circuits | 1500 |

Since a given circuit may be used as a link in a long built-up connection, consideration must be given to the number of links involved and each link designed so that it may be connected to any other link in the system. This requires that individual links must be somewhat shorter than indicated previously. The overall length for a given grade of transmission will also be affected by the amount of transmission loss allowed in the terminating trunks and loops. Undoubtedly future developments will materially extend the length over which it is practicable to talk with the present types of conductors.

Usually several plans are considered when a large addition to a plant, such as a toll cable, is indicated. Preliminary studies require an approximate electrical design of the circuits for each plan together with the cost of providing the facilities for a long period of years. The preliminary studies together with other basic data as presented by Mr. Chamberlin determine the plan to be adopted. After a particular plan has been adopted it is necessary to review the electrical design in order to determine the loading arrangement of the conductors, the location of repeater stations, and the equipments to be placed at each station from year to year.

Carrier-current systems are being used extensively in the provision of additional facilities. The increase in facilities possible on a given lead by this means has been indicated in the paper. Before a number of systems can be operated on a lead it is necessary to rearrange the wires by transposition to reduce the interference between systems. The present standard arrangement makes use of alternate crossarms. While, in general, the costs are such as to make the use of adjacent crossarms for multi-channel carrier-telephone operation undesirable, in special cases, the added expense may be justified by other considerations.

The single-channel system developed for use on short hauls may be placed on the flat phantom groups of adjacent crossarms since the interference between systems of this type is less than that between multi-channel systems which occupy a higher frequency range.

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# A Carrier-Current Pilot System
## of Transmission Line Protection
### A. S. FITZGERALD[1]

### INTRODUCTION

THE increasing complexity of modern transmission networks presents many difficult problems in connection with the design and application of protective relays.

On the larger systems, the use of increased time delay may be inadmissible on account of the difficulties met with in maintaining stable operation. Rather, there is a tendency in the direction of reduction in the time of operation of relays.

Thus, there is a growing interest in differential methods of protection; that is, in systems in which comparison is made between currents which under normal conditions are necessarily equivalent. These have the advantage of not being dependent upon the performance of relays in other circuits for their selective action.

The simplest form of differential protective arrangement consists of a circuit embracing a portion of a power system (such as a generator winding or transmission line), and registering any difference which may occur between the current entering or leaving the section protected.

Such arrangements offer very definite advantages over all other selective relay schemes, in that each section of the network so protected is a unit in itself and it is not affected by any other protective measure, nor by any alterations in the network arrangement. Thus no changes in the relay setting are necessary nor are these, in general, influenced by the direction of flow of power or fault current, nor by the settings of relays on connecting lines, as is the case with time delay overload protection. Moreover, in differential systems, faults may be cleared with a minimum loss of time.

These advantages are so marked that the differential system of protection is employed almost universally for the protection of generator windings, and similar applications where the extent of the circuit protected is a matter of yards rather than miles. For the protection of lines, however, the cost of the special pilot conductors has greatly restricted the application of this type of relay system, and it is not in general use in this country except for short distances or where there are so many sections in series that time delay methods are not desirable.

The success that has attended the use of differential pilot wire schemes in other countries, where the length of lines is less, indicates the desirability of a means of furnishing a similar service without the necessity of special conductors.

### CARRIER CURRENTS

The term carrier current is employed as descriptive of a-c. energy generated at frequencies which lie, roughly, between 10 and 200 kilocycles. At these frequencies, the transmission of electrical energy exhibits special characteristics due to which it is possible to superpose carrier-current-control circuits on transmission lines or cables.

Carrier current is conducted more or less freely by straight conductors, and is restricted thereto by breaks or open circuits, except in so far as capacity paths are provided by parallel lines situated in close proximity. Carrier current may be employed for control systems because circuits may be provided which will conduct the carrier current but which will not effectively pass 60-cycle power current, and by means of which the carrier current may be introduced into, or taken out of, a power system.

Conversely, the flow of carrier current can be restricted within certain specified limits by circuits which provide a high impedance to carrier current but do not affect power currents.

Carrier current energy is commonly generated by means of three-electrode tube oscillators.

### REQUIREMENTS OF A PROTECTIVE SYSTEM

A protective scheme suitable for association with carrier current operation and desirable from commercial and operating aspects, will preferably include the following features:

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[1] Radio Engineering Dept., General Electric Co.

*Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., September 13-16, 1927,*

1. The employment of potential transformers will be avoided.

2. The scheme should not require any definitely quantitative function on the part of the carrier apparatus since there may be variations in attenuation.

3. There should be no apparatus installed as part of the protective system which in itself represents an extension of the liability to trouble of the circuit protected. Current transformers of high safety factor, preferably of the bushing type, should be used. The carrier-current coupling equipment should be of the most reliable form available.

4. The equipment so far as possible, should be entirely current operated; that is, its operating power should be derived directly from the fault current.

5. Failure of the carrier-current apparatus should not render it possible for a fault to remain on the line thus disturbing the whole power system. Rather such a defect should advertise its presence by causing only the individual line to trip unnecessarily if overloaded.

6. The system should be suitable without modification for installation at any point in a network irrespective of possible direction of flow of fault current, etc.

7. It should be possible to check the carrier-current equipment at any time without interfering with service.

8. In view of the fact that a restricted range of frequency is assigned to control systems, only one frequency per line protected should be used.

## GENERAL PRINCIPLES

In its simplest form, differential protection consists of the installation of two current transformers at each extremity of the circuit embraced, one to receive the current entering the section, and the other, that leaving it. The secondaries are either connected in opposition and in series with one or more relays; or more usually connection is made so that the currents normally circulate, in which case the relays are connected across equipotential points. In either arrangement, the relays, normally, should receive no current, but on the occurrence of a fault, which will be a difference between the entering and leaving currents, a corresponding difference will appear in the relays. Numerous refinements and variations of this principle have been evolved in order to overcome difficulties in balancing and to render the apparatus immune from tripping on heavy "through" currents.

It will be perceived that the function of the pilot conductors is to furnish one end of the line with a sample of the current at the other end, in order to provide the relays with means of discriminating between sound and faulty conditions.

It is not, however, desirable to employ exactly similar principles when carrier current is to be used in place of a pilot line. This is due to the fact that carrier current is usually transmitted by means of resonant circuits. Because of this, and other causes, it is not always possible to achieve exact numerical ratio between the carrier current transmitted from one point and that received at another. Thus, it is preferable to avoid an arrangement in which fault conditions are indicated by a difference between the magnitude of the currents concerned.

A transmission line will be equipped with a circuit breaker at each end and with relays designed to trip the breakers automatically in the event of abnormal currents being carried by the line. The relays may operate on overcurrent, ground current, or may be power-directional. Such relays will correctly indicate abnormal conditions, but, in the general case, do not, by themselves, distinguish between a fault on the line—when we want both switches to trip—and a fault elsewhere, when we wish to avoid interrupting the line.

In order to accomplish this, we must know at each end of the line what is happening at the other end, and it is for this purpose that we employ the carrier-current system.

In ring systems, or networks, a fault generally not only causes a difference in the magnitude of currents entering and leaving the faulty line, but also sets up a difference in direction.

One method of carrier-current protection would be to employ power directional relays at each end and to use the carrier to furnish at one end an indication of the position of the relay contact at the other. Such an arrangement would be quite practical, but a system independent of line potential is to be preferred.

## PRINCIPLE OF OPERATION

The effect of a fault on the normal direction is the feature employed to discriminate. In order, however, to avoid potential excitation, the direction of power is not used, but instead, the instantaneous direction of current. This is done in the following way:

The carrier is not used to trip the circuit breakers when the line itself suffers a fault. If this were done, we could not be sure of proper operation if the line should be connected to a source at one end only; or if the line should break in such a way as to bring about this condition. Moreover, the carrier channel may be interrupted by the fault.

Thus, at each end, overcurrent relays are installed and connected to the oil-switch trip circuit. If the instantaneous currents at each end of the line have the same direction, indicating that the line itself is sound, a carrier signal is received preventing the overcurrent relays from tripping the circuit breakers. This looks after the stub feed, or broken line condition.

If a three-electrode tube oscillator be operated from an a-c. plate voltage, it will oscillate intermittently during those half cycles only when the plate is positive.

In a similar way a bias detector may be supplied with an a-c. plate voltage. It will be inoperative during the half cycles when the plate is negative, but during the positive half cycles, if the grid potential permits, plate current may flow. The grid will be excited from a source of 180 deg. out of phase with the plate voltage so that normally there will be no plate current, the grid being negative when the plate is positive. If there be impressed on the grid an additional voltage of carrier frequency, a rectified current may be caused to flow in the plate circuit; but this can occur only during a positive half cycle. Thus, we may have a transmitter sending during alternate half cycles and a receiver capable of receiving only during the intervening half cycles. A relay may be placed in the plate circuit of the receiver tube; this will operate when carrier is received.

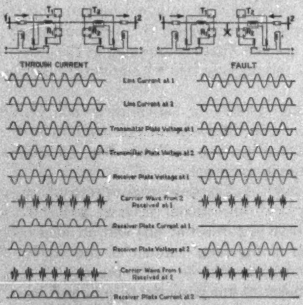
1
T1
R1
2
T2
R2
1
T1
R1
2
T2
R2
THROUGH CURRENT
FAULT
Line Current at 1
Line Current at 2
Transmitter Plate Voltage at 1
Transmitter Plate Voltage at 2
Receiver Plate Voltage at 1
Carrier Wave from 2 Received at 1
Receiver Plate Current at 1
Receiver Plate Voltage at 2
Carrier Wave from 1 Received at 2
Receiver Plate Current at 2

FIG. 1—PRINCIPLE OF OPERATION

Fig. 1 shows, in an elementary manner, how these features may be arranged to furnish the desired result. The diagram represents a transmission line having a circuit breaker and over-current relay at each end. The two ends of the line are designated as "1" and "2" respectively. Carrier-current transmitters $T_1$ and $T_2$, at each end, together with receivers $R_1$ and $R_2$, are excited from current transformer secondaries. When carrier is received, the receiver relays open the trip circuits and prevent the opening of breakers. The equipment at each end is the same except that, as shown, one of the current transformer secondaries is reversed.

The left hand series of diagrams refers to the case of a sound line which may be supposed to be carrying excess current to a point beyond the bus. It will be seen from the diagram that the primary currents are identical, whereas the plate voltages of the transmitters, which are derived from the current transformer secondaries, are of opposite polarity. The receiver-plate voltages at each end are reversed in respect of the adjacent transmitters. Thus the receiver voltages are also 180 deg. displaced from each other. Each receiver, therefore, is inoperative during the half cycle occupied by the transmission from the transmitter at the same end, and cannot receive from the latter.

Referring now to the transmitter-plate voltages at opposite ends, as shown in the left hand diagram, it can be seen that the positive half cycles occur alternately. Thus the two transmitters, oscillating intermittently, send out pulses of carrier in alternate sequence. The positive half cycles of the receiver-plate voltage are shown in full lines and the negative half cycles, when the receivers are inoperative, are shown in broken lines.

Therefore $R_1$ is inoperative while $T_1$ is sending, but can receive from $T_2$. Likewise $R_2$ can receive from $T_1$ but not from $T_2$. In the case illustrated by the left hand series of diagrams, both receivers are operated and the receiver relays open the trip circuit and thus prevent the over-current relays from tripping the circuit breakers.

The right hand series of curves shows the conditions when there is a short circuit on the line. In this case both the transmitters are sending simultaneously during which period neither of the receivers is able to receive. When both the receivers are operative neither of the transmitters is sending. Thus the receiver relays are not opened and the line is tripped by the over-current relays at each end. The operation of the system, therefore, is such that if a current enters at one end, that end will be opened automatically unless the current is "registered out" at the other end, which is an indication that the line is sound. If a fault be fed from one end only, the transmitter at the other end will not be excited by the current transformer and will not transmit. The fault will therefore be cleared, at the end from which it is supplied, by the over-current relay.

A unique feature of this arrangement is the fact that it is possible to send and receive in both directions at the same time and at the same carrier current frequency. Thus, only a single frequency is required instead of two. This is a distinct advantage if a number of lines is to be protected by this method, and one which will become more evident as the use of carrier current for purposes of communication and control becomes more prevalent.

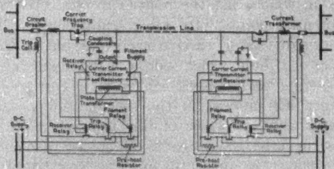
Bus
Circuit Breaker
Carrier Frequency Trap
Transmission Line
Current Transformer
Bus
Trip Coil
Coupling Condensers
Output
Filament Supply
Receiver Relay
Carrier Current Transmitter and Receiver
Carrier Current Transmitter and Receiver
Plate Transformer
Filament Relay
Filament Relay
D-C Supply
Receiver Relay
Trip Relay
Trip Relay
Receiver Relay
D-C Supply
Pre-heat Resistor
Pre-heat Resistor

FIG. 2—DIAGRAM OF CONNECTIONS—SINGLE PHASE

## SINGLE-PHASE CIRCUIT

The actual arrangements employed will now be more readily understood. Fig. 2 shows a complete diagram of the system. With a view to simplicity, only a single-phase line is given in the first instance, and the carrier current apparatus is not shown in detail. It will be seen that the current transformer is connected in series with the primary winding of the plate transformer and two over-current relays, one of which completes the trip circuit and the other energizes the tube filaments. The former is furnished with a slight, definite, time delay; the latter is instantaneous. A preheating resistance may be connected across the contacts of the filament relay if desired. If the filament be run continuously at reduced voltage, it will have little effect on the life of the tube, but the time taken to raise the filament to full operating temperature will be substantially reduced. If this be done, the time delay of the trip relay need not exceed one-half second. Without preheat, a full second might be necessary.

The trip relay will be set to pick up at a current slightly higher than the filament relay, in order to insure both filament relays closing before either trip relay picks up. The filament relays will be set to operate at a current somewhat exceeding the normal load on the line and not less than that at which the current transformers furnish sufficient plate voltage to operate the transmitting and receiving tubes.

Thus, when an overload occurs on the transmission line, the filament relay first picks up, closing its contacts which connect the filament supply to the vacuum tubes. Within the brief period, necessary for the filaments to reach operating temperature, the carrier-current equipment is fully in operation.

The receiving tube controls a polarized relay, the contacts of which are normally closed. When the carrier wave is transmitted during those half cycles which indicate that the over-current is not due to a fault on the line protected, the receiver tube energizes this relay. Thus, at both ends of the line, the trip circuit is opened and the subsequent closing of the contacts of the trip relays immediately afterwards does not open the circuit breakers.

If on the other hand the fault should be on the line itself, either the carrier does not reach the receiver, or if it is received, does not affect the receiver because it is transmitted, during the half cycles when the receiver is inoperative. The result is the same in either case; the receiver relay remains closed and when the trip relays close their contacts, the trip circuit is completed and the line disconnected.

It will be noted that the line has positive over-current protection under all conditions except when there is a definite indication that it is sound.

### CARRIER-CURRENT TRAP

An important point in the operation of this system is the affect on the channel of reference of faults. While the principle adopted has followed closely that of wired differential schemes, and the general effect of faults will be viewed from similar aspects, certain differences, due to the use of carrier, are of interest.

The occurrence of a fault may or may not lead to the interruption of the channel of reference; that is, the effective transmission and reception of the carrier wave. Assuming a simple coupling, the carrier will be stopped by a broken line, or a short circuit between the phases to which the carrier is coupled, on the section protected. A similar short circuit outside the protected zone may also have the same effect. Thus, it is necessary to provide between the point of coupling and the bus, a trap circuit for carrier. This prevents short circuits, anywhere but on the section protected, from interrupting the carrier. This trap circuit takes the form of a lightning arrester coil tuned, by means of a condenser, to the frequency of the carrier circuit. The condenser is mounted directly on the choke coil. It is made in the form of an assembly of several dissimilar capacities brought out to terminals in such a way that a large number of combinations may be obtained. In this way, the trap may be tuned to any one of a number of available frequencies. The condenser is arranged to be readily removed from the coil for this purpose.

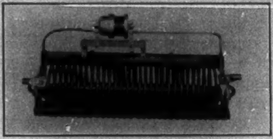

FIG. 3—CARRIER-CURRENT TRAP

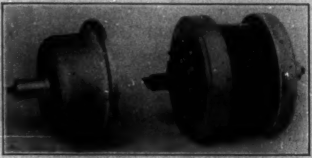

FIG. 4—CARRIER-CURRENT TRAP CONDENSER

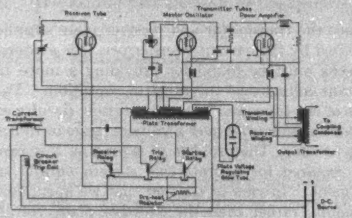

FIG. 5—CARRIER-CURRENT TRANSMITTER AND RECEIVER

The complete trap with the condenser in position is shown in Fig. 3. Fig. 4 shows the condenser dismantled for setting to the desired frequency. The condenser shown has three sections and can be set for 17 frequencies ranging from 40 to 120 kilocycles.

The complete connections for both the relay and carrier current circuits, at one end only, are shown in Fig. 5. Two secondary windings on the plate transformer are required to operate the carrier transmitter and receiver. The transmitter is of conventional form, having one master oscillator tube and one power amplifier, a suitable tap being furnished for the lower voltage required by the oscillator. The receiver is an ordinary bias detector, the negative voltage applied to the grid being derived from a tap to the transmitter winding, since this is of opposite polarity, at an instant, from that of the receiver plate winding.

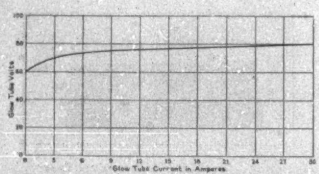

Fig. 6—Regulating Glow Tube Characteristic

### Plate Voltage Regulation

One of the principal features of any protective relay system is the extreme range of current value over which it must operate. The apparatus should preferably be capable of functioning with currents not greatly exceeding normal load; yet it must sustain without damage, and work properly at the heaviest short-circuit current which the power system can furnish. In extreme cases, twenty times normal load may be met with.

Since the transmitter and receiver plate supplies are furnished by the current transformer, it is evident that a means must be found for providing a more or less constant voltage over this range of excitation. Vacuum tubes of the type used in carrier-current circuits cannot operate satisfactorily over a voltage range of more than three to one. The problem of extending this range to that required for a protective system entails special treatment. In view of the fact that we must limit the maximum, rather than the effective plate voltage, in order that the tubes may not be damaged during short circuits on the power system, saturated core principles are of no assistance.

This difficulty has been successfully overcome by the use of a special type of regulating glow tube, developed by the company's research laboratory. The characteristics of this tube are shown in Fig. 6. The tube passes no current until the voltage reaches 60 volts, when a visible glow appears. For any value of current up to 30 amperes, the voltage drop across the tube will not exceed about 80 volts. The appearance of this tube may be seen in Fig. 7.

The glow tube is connected to a special secondary winding on the plate transformer, the action of the tube being illustrated in Fig. 8. As the primary current is raised, the voltage across the glow tube winding, and across all other windings on the transformer, will increase up to the point at which the tube commences to discharge. The values of the various plate voltages at this point and at higher values of excitation will be the glow tube voltage multiplied by the respective turn ratios. It will be noted that the tube controls the maximum voltage only and does not come into action until the instantaneous value reaches the glow voltage of the tube. The effect, therefore, on the wave form is to furnish a wave which is sinusoidal up to the point where the peak voltage is equal to the glow point of the tube. With higher values of excitation, there is no substantial increase in the maximum value of any of the secondary voltages, but the wave form becomes more and more rectangular. This characteristic is peculiarly favorable to this system of carrier current control in which the operation is independent of the wave form and of the amplitude, being solely determined by whether the wave is positive or negative.

Fig. 7—Plate Voltage Regulating Glow Tube

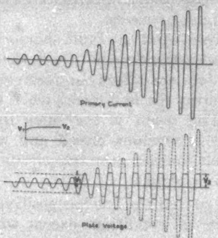

Fig. 8—Action of Glow Tube

Fig. 9 is an oscillograph record which shows the action of the glow tube. The primary current is varied over a wide range and the resulting effect on the plate voltage, which would be proportional to the current if no glow tube were present, can be seen very clearly.

### PHASE RELATIONS

In the explanation of the operating principles of this system, it was assumed that when the line is sound, the two currents will be in phase and that when the line suffers a fault, the instantaneous currents will be of opposite polarity. In the development of this system, it has been necessary to consider to what extent this is actually correct under service conditions.

FIG. 9—PRIMARY CURRENT AND PLATE VOLTAGE

In the case of a "through" short-circuit current, the currents at each end of the line are in actual fact identical, on lines of present length, except for the charging current of the line, which in most cases is small in comparison with the current at which the over-current relays would be expected to operate.

When the line itself suffers a fault, the two currents are not identical. They will usually be of different magnitude but will in general be very nearly 180 deg. apart in phase relations. There may be special cases, however, where the fault is fed from each end through circuits having different impedance power factors which may result in some slight departure from this phase relation, and this possibility has been studied. Fig. 10 is a polar curve which shows the affect on the current in the receiver relay of variation in the phase relation between the primary currents exciting the transmitter and receiver. It is evident that in the case of a "through" short-circuit current, there is no risk of the receiver relay failing to pick up as the currents are identical. In the case of a short-circuit on the line, the relay should not pick up. It can be seen that there must be a difference of at least 45 deg. between the two currents before this can occur.

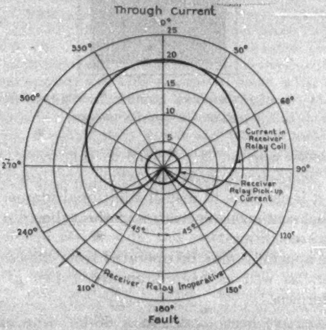

FIG. 10—EFFECT OF PHASE RELATION BETWEEN RECEIVER AND TRANSMITTER

### THREE-PHASE CIRCUIT

In order to apply this arrangement to the protection of a three-phase line, it is not necessary to use three carrier current equipments. All that is required is to furnish an arrangement of primary windings such that any possible fault condition will energize the plate transformer.

It will be necessary to bring the carrier apparatus into action on the occurrence of the following currents. We may refer to the three phase as A, B, and C.

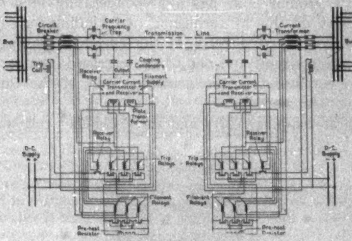
Bus
Circuit Breaker
Carrier Frequency Trap
Transmission Line
Current Transformer
Bus
Trip Coil
Coupling Condensers
Output
Receiver Relay
Filament Supply
Carrier Current Transmitter and Receiver
Carrier Current Transmitter and Receiver
Plate Transformer
Receiver Relay
Receiver Relay
D-C. Supply
D-C. Supply
Trip Relays
Trip Relays
Filament Relays
Filament Relays
Pre-heat Resistor
Pre-heat Resistor

FIG. 11—THREE-PHASE DIAGRAM OF CONNECTIONS

| | |
|---|---|
| Three-phase fault on | A B C |
| Fault between lines | A B |
| Fault between lines | B C |
| Fault between lines | A C |
| Ground fault | A |
| Ground fault | B |
| Ground fault | C |

The minimum number of exciting windings which will enable each of these conditions to furnish energy is three. By providing, therefore, three windings, of dissimilar numbers of turns, each of the above cases will set up a resultant excitation of the transformer. The magnitude of this resultant will necessarily vary according to which of the above conditions holds. Since, due to the glow tube, the carrier-current system operates over an exceptional current range, this variation will be of no moment, provided that the minimum excitation,—that is, when the least effective combination of turns results,—is sufficient.

It is very often an advantage to be able to furnish more sensitive operation in the case of ground faults than where the trouble arises from a short between lines. Moreover, a ground fault, limited in magnitude, perhaps, by an earthing resistance or maybe by the high reactance or resistance of the abnormal return path, may not cause complete reversal of the current if an appreciable load is present.

Thus, it may be desirable to so arrange the means whereby the flow of current controls the carrier apparatus that a ground fault has a preponderating influence. We may do this by furnishing two windings of equal turns connected directly in the current transformer secondary circuit and one of an increased number of turns connected in the neutral circuit of the three-current transformers.

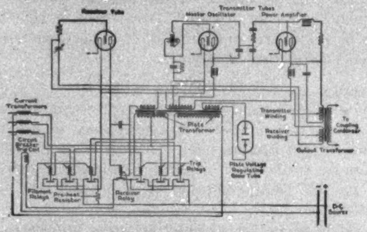
Receiver Tube
Transmitter Tubes
Master Oscillator
Power Amplifier
Current Transformers
Circuit Breaker Trip Coil
Plate Transformer
Transmitter Winding
Receiver Winding
To Coupling Condenser
Output Transformer
Trip Relays
Plate Voltage Regulating Glow Tube
Filament Relays
Pre-heat Resistor
Receiver Relay
- +
D-C Source

FIG. 12—CARRIER-CURRENT TRANSMITTER AND RECEIVER—THREE PHASE DIAGRAM

Three tripping relays and three filament relays are employed. In each case, one may conveniently be a ground relay which may be set to operate at a lower value of overload than the others. The general arrangement is shown in Fig. 11.

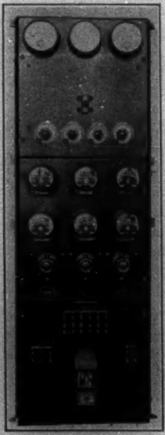

FIG. 13—CARRIER-CURRENT AND RELAY PANEL

The complete connections for one end only are given in Fig. 12. It should be noted that the glow tube is energized by all kinds of faults. Therefore, while the primary current at which the glow tube comes into operation will vary according to the nature of the fault, the glow tube will always regulate all the plate and other voltages at the appropriate values corresponding to the turns on the several windings.

## CONCLUSION

This system will furnish protection substantially equivalent to that which may be obtained with a pilot wire system, provided that the lowest phase-fault current at which it is desired to operate, is not less than the normal rated current of the line. In the case of ground faults, it is possible to obtain operation at lower values than full-load current.

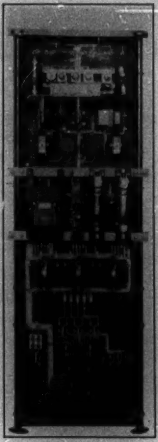

FIG. 14—CARRIER-CURRENT AND RELAY PANEL, REAR VIEW WITH COVER REMOVED

In cases where it is required to take care of phase-fault, short-circuit currents, which are less than full load, it is desirable to install additional filament relays to avoid continuous operation of the tubes during normal load conditions.

The apparatus may be operated from bushing transformers as well as from standard types of current transformers.

Tests have been made on a 66-kv. line about 30 mi. in length. The apparatus was excited from standard bushing transformers. Actual short circuits, both between phases and to ground, were applied to the line itself or at neighboring locations. The system performed satisfactorily with fault currents which ranged from 200 to 1700 amperes.

Fig. 13 shows a front view of the equipment which was employed for these tests. The upper section of the panel carries all the carrier-current transmitter and receiver apparatus and instruments indicating the filament voltage of the tubes, the transmitter output current and the receiver relay current. The tuning adjustments can be seen in the photograph.

On the middle section are the filament relays, trip relays, and filament rheostats.

The receiver relay is mounted on the lower section which also carries the filament and test switches.

The carrier apparatus may be seen more clearly in the rear view Fig. 14. This section is normally protected by a cover. Back of the center section are mounted the plate transformer and the plate voltage regulating glow tubes of which two are shown in the illustration.

## Discussion

**E. R. Stauffacher:** This novel and effective system of transmission-line protection offers great promise for lines operating at high voltage with a long-distance between stations.

It was my privilege last March to witness some of the tests of this equipment on the Ohio Power Company's system in the section of the system located near Zanesville and between the substations known as Newmark and Crooksville. This carrier-current pilot system of protection was applied to a 66-kv. line between the above stations and the stations were separated a distance of 35 mi. The tests were made on a rainy Sunday, and fourteen tests in all were made by means of putting short circuits within the section protected, and exterior to the section protected. The short circuits were phase-to-phase and phase-to-ground. There was, with possibly one exception, successful operation in all cases. When the short circuits were applied exterior to the section protected, the carrier-current system of protection kept this section in service; when the short circuit was within the section protected it eliminated this section and the short circuit promptly from the system.

One of the tests was particularly outstanding,—Test No. 6. This was a phase-to-phase short circuit between phases 1 and 2, was exterior to the section protected, and was rather severe, the current from one side of the system being 285 amperes, at 66 kv., and from another side 1785 amperes at 66 kv. The total amounts to a short circuit of about 230,000 kv-a.

While that is not so great as may be encountered on this system, still it is a sizable short circuit and for that particular system was enough to result in a very heavy jolt. It was quite interesting to notice the swaying or oscillation of the system for several seconds after the short circuit occurred. I believe that about 10 swayings were observed, swinging back and forth on the ammeter, where thousands of kilowatts were being exchanged across the section protected by this carrier-current protective system—and this section remained intact and stayed in service.

That would have been a very severe test for any directional-relay form of protection, and I doubt if the lines would have stayed in, for the current was sufficiently great to indicate that the short circuit was in that particular section, and the direction of current flow was from one side to the other.

The carrier current was apparently fast enough to keep up with the swayings back and forth, and the section did not trip out.

In conclusion, as I stated before, it appears to me that this system offers great promise. From the observation of the tests it looks as if there was something to be desired in regard to speed. The author informs me that the speed of operation can be increased appreciably by the preheating of the filament and continuous excitation of the plate.

In this particular test 50 per cent preheating of the filament was used, but the time can be cut down, by means of 100 per cent heating of the filament. Here is a case where it is necessary to balance the life of the tubes against the necessity for extra speed in eliminating trouble from the system. We are finding out that the elimination of a fault from the system without making the system unstable, is largely dependent upon speed and my only suggestion to the manufacturers is that they do all they can to speed up operation of this very unique system of differential protection.

**Roy Wilkins:** (by letter) In protection against line faults there are two major conditions:

1st: Where the short-circuit current, either between the phases or from phase to ground, is several times the normal load current, such as is found in distribution systems in metropolitan areas.

2nd: Where the short-circuit currents are comparable to, or less than, the normal current in the line. Such conditions apply to high-voltage transmission lines, particularly with regard to current from phase to ground, the case most common in practise.

The paper by Mr. Fitzgerald presents a method beautifully simple for applying differential protection to transmission lines. Differential protection has been developed to its highest perfection in England, and a general study of the English methods, difficulties, and results is valuable to anyone interested in relays.

I should like to point out from a practical standpoint some of the difficulties that will be encountered before the carrier-current pilot system can be universally applied to large high-voltage networks. Judging from considerable carrier-current experience with all available present-day makes on extreme high-voltage lines it can be stated that at present existing relay systems are far more reliable than carrier-current installations.

In view of its extra cost, the carrier-current installation to be desirable must give superior performance. Some means must be secured to eliminate the phase-relation troubles mentioned in the paper, because the charging current on a 200-mi. 220-kv. line is often half as great as full-load current, and at low or medium loads may be more than the in-phase current at either end of the line, depending on operating conditions.

It is a perfectly practical condition to have more than 45 deg. between such currents for normal conditions. Lower-voltage networks have relatively little of such troubles.

Another difficulty is that the current in phase-to-ground short circuits greatly varies in power factor, depending upon the location and character of the trouble.

Relays at present in use for ground protection are so connected as to trip in a given direction selectively on as low as ¼ sec. and on the Pacific Gas & Electric system of some 5000 mi. of line, 60-kv. and above, last year, for over 1500 operations, there was no indication of a faulty operation of a ground relay.

Phase relays depending upon combinations of voltage and current do not present nearly so clean-cut a record.

Finally, the operating time must come down from the present standards—a very great way down,—as a perusal of several of the high-tension papers presented will show.

Differential protection is one of the most desirable forms known, and outside the various split conductors and enclosed pilot wires used on low tension, the carrier system is the initial attempt to adapt it to high tension. It is to be hoped that it can be developed to overcome most, if not all, of its present limitations.

**Philip Sporn:** (by letter) As pointed out by Mr. Fitzgerald, the differential method of protection of generator and transformer windings has become almost universal and is the only standard and proper method of protecting these important pieces of equipment. The use of the differential circuit in protecting buses has also come very prominently to the foreground within the last four or five years. Abroad, the differential scheme has been employed to protect transmission lines but it has never found very much favor here and in the main I believe this instinctive engineering act, if you wish to call it that, has been fully justified. If a pilot line is made more reliable than the transmission line, and it must be that to stand up under conditions that would cause the breakdown of the transmission line, then the cost involved becomes so great that economically it becomes prohibitive. If it is not to be built with the same degree of reliability then it is of no use to go to the scheme. The use of carrier eliminates the main reason why the pilot scheme has not found favor here up till now.

To those of us who have had actual experience in trying to obtain selective action on a loop involving four or five, and sometimes six, stations, by the use of reverse-power and induction-type relays only, and who have actually been trying to obtain another 10 cycles differential between two stations, and have known the disappointment that goes with chasing through a set of relay time settings only to find at the very end that there is one condition under which the apparently perfect set of settings would not work, the idea of getting a method of cutting down by one or two, the number of stations that would have to be made so to differentiate will certainly be welcome.

It is hoped that actual operating experience will bear out all the fond hopes that we have for this scheme. On this, as well as on the question of tests referred to by Mr. Fitzgerald, we may have something to place before the Institute within the next year or so.

One other aspect of the differential scheme of protection that ought to be pointed out is the lightning aspect.

Operating experience obtained within the last four or five years on systems where, under conditions of short circuit or flashover, currents in the neighborhood of 3000 to 5000 amperes can be pumped into the point of flashover on a transmission wire, has definitely shown that if the trouble is cleared within a certain minimum time, little burning, if any, will result. I think it can be definitely stated that on systems such as mentioned, if this time is kept below 1 to 1½ sec. no trouble need be anticipated. Further, if the time is made as high as 3½ sec., trouble is to be expected almost always. Now here is an arrangement that in a loop system allows the clearing of a case of trouble within a period say of $^1/_2$ to $^2/_3$ sec. The contribution of such a device to continuity of service, if it develops satisfactorily, is bound to be enormous.

**L. F. Fuller:** A protective gap is placed around the carrier-current trap so that surges on the transmission line will not pass through the trap but will jump the small gap and pass on. This gap is not shown in Figs. 2 and 11 of the paper.

**A. S. Fitzgerald:** Mr. Stauffacher has made reference to the speed of operation of this form of protective apparatus. In the first trial installation of this system no especial effort was directed toward attaining any great speed of tripping. We concerned ourselves mainly with an investigation of the operating characteristics of carrier current in this new field of application.

As Mr. Stauffacher indicates, the speed of tripping of this apparatus is not limited to the half-second mentioned in the paper, where reference was made to a circuit in which the over-current relays, which initiate the operation of the carrier-current equipment, were connected so as to control the filament voltage.

Substantial reduction in time can be obtained if, instead, we connect these relays so that they complete the plate-voltage circuit instead of the filament supply. This is now being done in the case of the equipment which the paper describes. The filaments are run continuously, but since the plate voltage is not normally applied to the tube, no emission can take place except when the protective equipment is actually brought into operation. The life of the tubes, of course, depends largely upon the length of time during which there is emission from the filaments.

Mr. Wilkins restricts his remarks to the conditions which are encountered when this system is applied to very high-voltage lines. It is assumed that he has principally in mind systems operating at 220 kv.

Mr. Wilkins entertains some doubt as to the reliability of carrier-current equipment. The number of carrier-current communication installations now in service in the United States on systems up to 132 kv. must exceed 200, and this figure surely suggests that a high order of reliability has been attained. The amount of carrier-current equipment at present installed on 220-kv. lines does not seem sufficient for final conclusions to be drawn as to the results which can be obtained at this voltage. Mr. Wilkins will also appreciate that the function which the carrier current is called upon to perform, is, in the present application, very much simpler than that necessary in the case of carrier-current telephony. There is no question of calling, nor are there any problems of modulation. Furthermore, the transmission of carrier is restricted to the simplest case of a single length of line instead of having to carry right across a complicated network.

The author finds himself in agreement with Mr. Wilkins when he points out that the application of carrier-current protection to 220-kv. circuits will involve the consideration of conditions not met with at lower pressures, and especially in respect to his remarks on the advantages of ground relays in comparison with phase relays. It is not unlikely that the ultimate solution will be found in a carrier-current system envisaging ground faults principally, if not exclusively.

The question of current-phase relation is, perhaps, rather too involved to discuss through the present medium but it may be pointed out that the curve given in Fig. 10 is the result of specific design based upon an estimate of the probable general condition. It is possible to furnish different characteristics if circumstances should require them.

The author shares with Mr. Sporn the hope that this system may ultimately prove to be a real help in the operation of large power systems.

# Coupling Capacitors for Carrier Current Applications

BY T. A. E. BELT[1]

Member, A. I. E. E.

***Synopsis.***—*Coupling to high-voltage transmission lines for purposes of carrier-current communication was first universally made by means of coupling wires. This type of coupling usually required high-power transmitting equipment, but when coupling capacitors were substituted it was possible to reduce the carrier input to the line without affecting the received signal strength. The paper gives an approximate method for determining the effectiveness of coupling wires and coupling capacitors. No attempt is made at refinements in calculations as it is only desired to show the effect of stray capacity. Curves show the change in practise from coupling wires to coupling capacitors. It is estimated that by the early part of 1928 the total number of the two types of coupling will be equal. The electrical characteristics for different types of insulation used in coupling capacitors, based on test results is given. Some important points of design for the new cable capacitor are included.*

* * * * *

## APPROXIMATE METHOD FOR DETERMINING EFFECTIVENESS OF COUPLING

A simple mathematical treatment only is necessary to show the effect of stray capacity. From experimental data it has been determined that the impedance of a single long transmission line to carrier frequencies is of the magnitude of the surge impedance of the line, and that this high-frequency impedance acts as a straight ohmic resistance load. It has also been shown that ground losses are relatively small for interphase coupling. In the following calculations, therefore, the carrier-frequency impedance of the transmission line will be treated as a resistance and the ground resistance will be neglected.

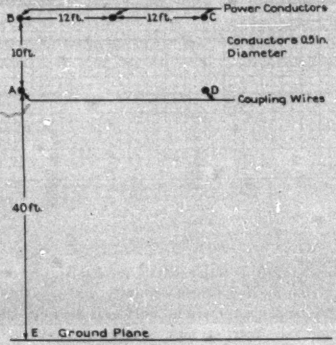

FIG. 1—DIAGRAMATIC ILLUSTRATION OF COUPLING-WIRE INSTALLATION

Fig. 1 is a diagramatic representation of a coupling wire installation. It is assumed that the power conductors are horizontally spaced on 12 ft. centers and the two coupling wires are 10 ft. below the two outside power conductors. The ground plane is assumed to be 40 ft. below the coupling wires. For such a coupling-wire installation, the useful capacity between a 1500-ft. coupling wire and the power conductor is approximately the capacity between $A\ B$ minus the capacity of $A\ C$, which is:

$$C_2 = 0.00205 - 0.00178 = 0.00027\ \mu\text{f.}$$

The stray capacities $A\ D$ and $A\ E$ between the coupling wires and to ground are of the order of 0.0018 $\mu$f. The equivalent circuit of this coupling-wire installation is represented in Fig. 2.

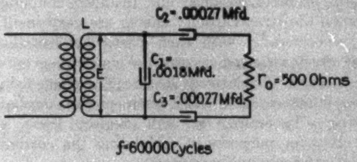

FIG. 2—EQUIVALENT CIRCUIT FOR COUPLING-WIRE INSTALLATION

Let

$f$ = Carrier frequency
= 60,000 cycles.
$E$ = Applied carrier-frequency potential
= 100 volts.
$C_1$ = Stray capacity between coupling wires and ground
= 0.0018 $\mu$ f.
= 1470 ohms at 60,000 cycles.
$C_2$ = Effective capacity of one coupling wire to the power conductor.
= 0.00027 $\mu$ f.
= 9800 ohms at 60,000 cycles.
$C_3$ = $C_2$
= 0.00027 $\mu$ f.
= 9800 ohms at 60,000 cycles.
$r_0$ = Equivalent high-frequency resistance of the transmission line.
= 500 ohms.
$Z$ = Impedance using coupling wires.

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[1] Engineer, General Electric Co., Schenectady, N. Y.

*Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., Sept. 13-16, 1927.*

$Z^1$ = Impedance using coupling capacitors.

Then for coupling wires (Fig. 2):

$$\dot{Z} = \frac{\dot{Z}_1 \dot{Z}_2}{\dot{Z}_1 + \dot{Z}_2}$$

Where

$$\dot{Z}_1 = o - j\,1470$$

$$\dot{Z}_2 = 500 - j\,(2 \times 9800) = 500 - j\,19600$$

Then

$$\dot{Z} = 67.4 - j\,1360$$

And

$$Z = \sqrt{67.4^2 + 1360^2}$$

$$= 1360 \text{ ohms.}$$

Therefore

$$I = \frac{E}{Z}$$

$$= \frac{100}{1360} = 0.0737 \text{ amperes fed into network}$$

where coupling wires are used.

With properly designed and installed coupling capacitors, the stray capacity effects are very small and vary considerably with each particular installation. By properly arranged circuits, the capacitance between lead-in wires is relatively small. The stray field between units is also small with proper mechanical spacing. Therefore, we will neglect these stray capacities for purposes of calculating the current required using coupling capacitors.

Fig. 3 represents the equivalent circuit for a coupling-capacitor installation. In order that the calculations may be compared directly with those obtained using coupling wires, the same effective coupling to the power conductor is assumed as before.

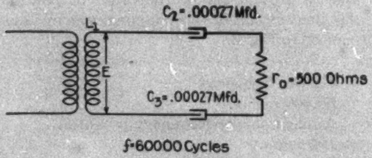

FIG. 3—EQUIVALENT CIRCUIT FOR COUPING-CAPACITOR INSTALLATION

Thus for coupling capacitors (Fig. 3):

$$\dot{Z}^1 = 500 - j\,19600$$

$$Z^1 = \sqrt{500^2 + 19600^2}$$

$$= 19600 \text{ ohms.}$$

Hence

$$I^1 = \frac{E}{Z^1}$$

$$= \frac{100}{19600} = 0.0051 \text{ amperes fed into network}$$

where capacitors are used.

We will define the effectiveness of coupling as a per cent ratio:

$$Y = \frac{\text{Useful Current}}{\text{Total Current}} \times 100$$

Then

$$Y = \frac{0.0051}{0.0737} \times 100$$

$$= 6.92 \text{ per cent for coupling wires.}$$

$$Y^1 = \frac{0.0051}{0.0051} \times 100$$

$$= 100 \text{ per cent for coupling capacitors.}$$

As previously stated, there is a small stray-capacity effect when coupling capacitors are used and, therefore, the effective coupling is not actually 100 per cent, but is believed to lie somewhere between 80 and 100 per cent.

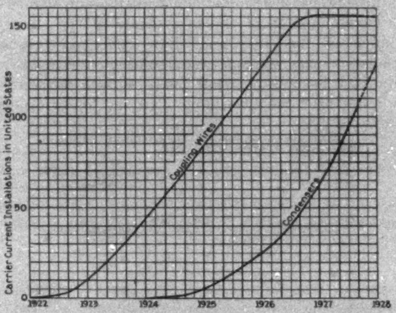

FIG. 4—CURVES SHOWING NUMBER OF CARRIER-CURRENT INSTALLATIONS, USING COUPLING WIRES AND COUPLING CAPACITORS IN THE UNITED STATES

### CHANGE IN COUPLING PRACTISE

From the relative effectiveness of coupling wires and coupling capacitors, it is not surprising that the change in practise from coupling wires to capacitors has been rapid. Up to the beginning of the year of 1924 there were no coupling capacitor installations in the United States. Fig. 4 shows the number of carrier-current installations using coupling wires and capacitors. Out of a total of 43 installations at the beginning of the year of 1924, all used coupling wires. At the end of 1924, there were 11 installations using capacitors and 97 using coupling wires. At the close of 1927, it is estimated there will be 130 installations using coupling capacitors and 145 installations using coupling wires; and that in the early part of 1928 there will be as many carrier-current installations using coupling capacitors as those using coupling wires.

## Types of Coupling Capacitors

Four distinct types of coupling capacitors are manufactured in the United States:

1. Mica
2. Porcelain
3. Oil Filled Cable
4. Oil Filled Tank

Both the mica and the porcelain type use low-voltage unit construction, that is, the individual units are rated at a definite voltage and capacity. For higher voltage installations series-parallel combinations are used for obtaining the proper voltage and capacitance rating. Some of the characteristics of capacitors, using these different types of dielectrics, are tabulated as follows:

TABULATION OF TEST DATA TAKEN ON 0.001 μf. COUPLING CONDENSERS USING VARIOUS TYPES OF DIELECTRICS

| Condenser | Type insulation | Voltage rating | Power-factor per cent at 1000 cycles | Flashover 60 cycles wet r. m. s. volts | Flashover 60 cycles dry r. m. s. volts | Impulse Strength Crest kv. | Impulse ratio |
|---|---|---|---|---|---|---|---|
| 1 | Mica | 110,000 | 0.10 | | 585,000 | 800 | 0.97 |
| 2 | Porcelain | 132,000 | 1.670 | | 284,000 | 300/400 | 0.75/0.99 |
| 3 | Oil-filled cable | 110,000 | 0.500 | 293,000 | 319,000 | 800 | 1.78 |
| 4 | Tank type (oil and barriers) | 110,000 | 0.500 | 260,000 | 355,000 | 1000/1100 | 1.99/2.19 |

On account of lower first cost for medium voltages, the mica and porcelain capacitors have been generally installed on circuits up to and including 66 kv. The oil-filled cable capacitor has a field of application for potentials above 66 kv. The oil-filled tank capacitors are available for 110-kv., 132-kv., and 220-kv. circuits. The 100-kv. and 220-kv. sizes have been in service for a period of approaching two years on several systems throughout the country. Both the Pacific Gas and Electric and Southern California Edison systems are equipped with 220-kv. capacitors.

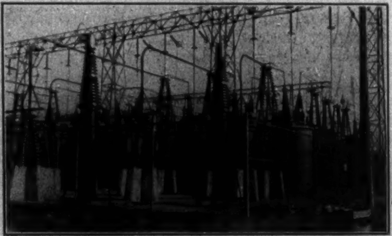

Fig. 5—Tank-Capacitor Installation on Southern California Edison System

## Cable Capacitors

The cable and tank[2] capacitors, Fig. 5, are new developments. The cable capacitor, Fig. 6, consists of a short length of paper-insulated oil-filled cable bent into a loop, the free ends of which are stripped of their lead sheaths and brought up through wiping sleeves and electrostatic shields into a porcelain shell, where they terminate in a common terminal. The lead sheath of the cable is attached to the carrier-current output transformer. The whole structure is filled with vacuum-treated oil and hermetically sealed from the atmosphere, so that changing weather conditions do not affect in any way the dielectric strength of the insulation. An expanding metallic reservoir is attached to the capacitor which takes care of the expansion and contraction of the oil caused by temperature changes.

Fig. 6 is a cross-section drawing showing the general details of construction of the cable capacitor for 110,000-volt service.

These capacitors may be mounted on the transmission tower by providing a suitable structural-steel bracket, placed on a base mounting as shown in Fig. 6A, or set up on a framework depending upon the particular requirements of the customer. In the majority of cases the operator will wish to mount the unit outdoor on the steel transmission tower, since the weight of the capacitor—1000-lb.—permits this, and it may be thus placed in a very convenient position at a minimum cost. Connection to the line is then simple and direct; the unit is far enough up so that no surrounding fence is

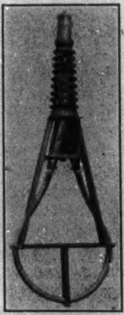

Fig. 6—Cable Couping Capacitor for 110-Kv. Transmission System

required to protect against marauders, and periodic examination is not handicapped.

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[2] For purposes of brevity it has been necessary to omit the description of the tank capacitor but it is planned to present a paper on this type of capacitor at a later date.

The voltage of cable-type capacitors is limited only by the voltage rating of available cable. At the present writing, the highest voltage commercial cable is 132 kv., but 154-kv. cable is now being built for capacitors of this rating, and specifications on 220-kv. cable for a proposed 220-kv. cable-type capacitor have been prepared. For the time being, it is not contemplated that the cable-type capacitor will be developed for voltages below 66 kv. because at the lower voltages the cost is higher than for some other types of capacitors.

The porcelains used on these units are similar to those used for standard oil-filled bushings for power apparatus; so that uniformity of practise in this respect is preserved.

At first glance it might appear that cable capacitors have considerable inductance due to the loop of cable, but a little thought shows that there is no external magnetic field if connection to the lead sheath is made at the top, for then at every cross-section of the cable the current in sheath and conductor is of the same magnitude, and the magnetic flux is therefore confined to the space between conductor and sheath. On the assumption of a linear distribution of current from the terminal to the low point of the cable loop where the current is zero, (for reasons of symmetry), the total stored magnetic energy corresponds to an equivalent inductance equal to only 1/12th that between the conductor and sheath of the active length of cable employed. This is about $5 \times 10^{-9}$ henry per ft.

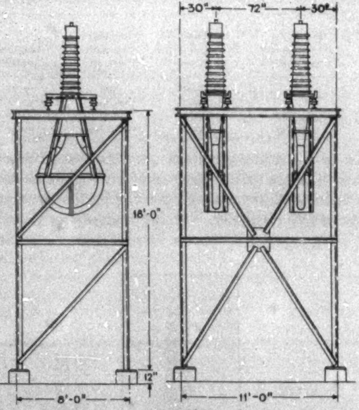

FIG. 6A—FRAMEWORK MOUNTING FOR CABLE CAPACITORS

The specially treated paper used in the construction of this cable gives it a capacitance of about $73.2 \times 10^{-6}$ $\mu$f. per ft. Therefore less than 14 ft. of cable has

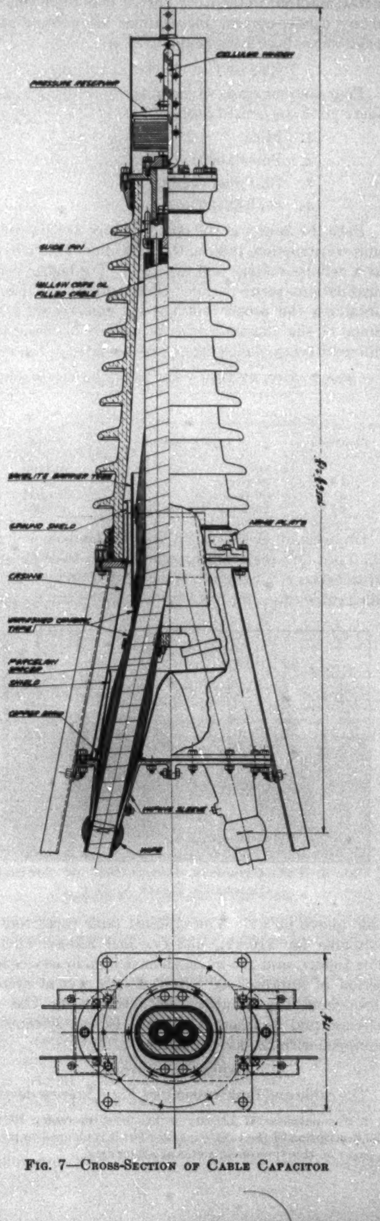

FIG. 7—CROSS-SECTION OF CABLE CAPACITOR

the required capacitance of 0.001 $\mu$ f. for coupling purposes. From 75 per cent to 85 per cent of the total capacitance is in the external loop of cable for the 0.001 $\mu$ f. units.

In the manufacture of cable capacitors it is important that the bending of the cable be done without wrinkling the paper dielectric. For this reason bending forms are used for shaping the cable loop. The transition from the several lead sheaths of the cable is effected by applying (on a taper) varnished cambric tape overlaid with copper braid until a diameter is reached at which a layer of oil may be introduced without exceeding the allowable radial gradient for oil, see Fig. 8. At this diameter a smoothly flared conical shield continues the metal surface until it intersects the wall of the casing. The function of this shield is to increase the thickness of the oil layer at such a gradual rate that excessive longitudinal stresses are avoided. When the flare of the shields has opened out to a sufficient diameter, the varnished cambric is again tapered down to the surface of the cable paper. A small porcelain spacer is inserted to preserve the proper spacing and then a double wrapping of varnished cambric tape applied to serve both as a mechanical binder and to relieve the radial stress on the oil, which increases as the ground shield inside the bushing shell is approached.

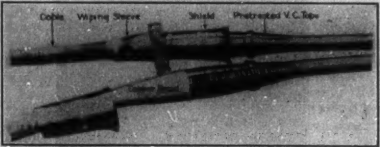

Fig. 8—Internal Construction of Cable Capacitor

The sheet-iron casing is oval shaped at the bottom where it bolts to the wiping sleeves, and then gradually changes to a circle at the top where it meets the bushing shell. The shape and dimensions of this casing have considerable influence on the design. The slope of its walls must not differ enough from the slope of the insulation to cause excessive longitudinal gradients, and must have sufficient clearance to prevent excessive circumferential stresses.

It is important that there always be a positive oil pressure inside the capacitor, so that no air or moisture can enter. For this purpose a pressure reservoir, actuated by an internal mechanism, keeps the oil under a pressure *above* that of the atmosphere. The reservoir is filled at the factory in such a manner as to compensate for the yearly temperature variation at its destination.

On the end castings of the pressure reservoirs there are four small radially projecting guides, which center the reservoir inside its sheet-iron cover. This cover has two celluloid windows through which the position of the reservoir may be observed. A terminal is welded to the top of the reservoir cover, for connection to the transmission line.

### Vacuum Treatment and Oil Filling

In a piece of apparatus of this kind intended for satisfactory operation over an indefinite period of time without attention, except for an occasional inspection, it is of primary importance that its interior insulation be absolutely free from moisture and air. For this reason, hermetically sealed cable capacitors are subjected to a very elaborate and efficient system of factory inspection and vacuum treatment. The bushing shell, casing, and pressure reservoir are individually tested with oil under pressure. During assembly every precaution is taken to keep the internal parts clean and free from moisture or foreign material.

When the capacitor has been assembled, a connection to a vacuum pump is made at the top of the bushing, with the pressure reservoir removed. A vacuum of 200 to 500 microns[3] absolute pressure is maintained during the treatment, at the end of which the capacitor is ready for filling with No. 10-C transil oil at 120 deg. cent. which has been kept at that temperature and under vacuum for 20 hours previous to the filling of the capacitor. This oil must test 30 kv. or better between one inch diameter disks spaced 0.1 in. apart.

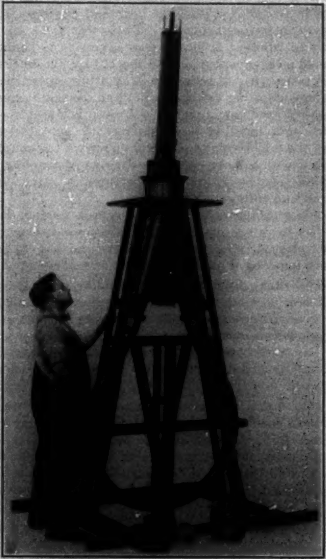

Fig. 8a—Partially Assembled Cable Capacitor

During the entire vacuum treatment the temperature of the cable is maintained at 100 deg. cent. on the outer lead sheath and at about 140 deg. cent. on the conductor by circulating currents in the cable as the secondary of a transformer.

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[3] There are 25,000 microns per inch of mercury.

The filled capacitors are allowed to cool for several hours under a pressure head of 5 lb. per sq. in. After cooling, they are disconnected from the oil and vacuum system and hermetically sealed with their pressure reservoirs. Before sealing, the reservoirs are expanded by oil pressure to the necessary height.

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## Discussion

**E. R. Stauffacher:** Fig. 5 shows the installation of the tank-type of coupling capacitors at the Laguna-Bell Substation of the Southern California Edison Company. There is a similar installation at Big Creek No. 3 which totals four units of capacitors for the system. In both of the stations the units are connected to one of the two 220-kv. busses. This equipment has been in service for about a year and has been thoroughly satisfactory in its performance. There was some apprehension at first as to whether or not it was advisable to connect a new and untried piece of equipment to the 220-kv. bus but our experience shows that it is as reliable as any other apparatus designed for the same operating voltage. You can see that it gives a much more finished and workmanlike job than is possible with overhead wire coupling. It is of interest to note the statement regarding the effectiveness of coupling where the coupling wires are credited with a 7 per cent effectiveness of coupling while the effectiveness of the coupling capacitors is rated somewhere between 80 and 100 per cent.

The cable coupling capacitor has not been used on our 220-kv. line and we have no experience to relate concerning it. However, for voltages lying between 66 kv. and 154 kv., it should prove to be a means of making an effective and compact coupling.

**Wm. Dubilier:** (by letter) I should like to point out certain facts concerning condensers for high-voltage operations:

There is no question as to the superiority of mica as a dielectric in a condenser over any other dielectric at present available. It must be remembered that mica is the only dielectric known which does not deteriorate with time, under electrostatic pressures.

Mica condensers are so constructed that the potentials are subdivided in such a way that individual units carry 1000 volts or less; therefore, the high-voltage problems, such as ionization in the condenser unit, corona effects and other difficulties that may be developed due to impurities of artificial dielectric material, as used in cables and porcelain, are not present with mica.

For the purpose of carrier-wave coupling, the mica condenser has been standardized in units of 22,000 volts. For higher voltages a number of those units is connected in series, eliminating the use of extremely high-voltage insulators necessary with all other types.

Moreover, this unit construction permits keeping only one or two units as spares, requiring considerably less investment, as compared to the types where the condenser unit is designed for line voltage.

Conditions in Europe, especially in territories surrounding Switzerland, are much more severe than are generally experienced in this country, and the electric railroads and power supply companies (such, for instance, as the Chemin de fer du Midi) have been experimenting for many years with every known insulating material, and have finally adopted mica condensers as the most suitable in practically all of their installations operating at 60,000 volts. These capacitors have now been operating with great satisfaction for several years.

A carrier-wave coupling condenser developed in this country is shown in the accompanying Fig. 1. The four separate units are clearly seen mounted on top of each other. Such an installation would be suitable for 88,000 volts; for higher voltages units might be added, one for each 22,000 volts.

Fig. 2, herewith, shows an actual installation at the Sunnyside Substation, Ohio Power Company, Canton, Ohio, one of the properties of the American Gas & Electric Company, installed on their 132,000-volt circuit between Canton, Ohio, and Philo, Ohio, March, 1925. This installation consists of two columns, six 22,000-volt units in series per phase.

FIG. 1—MICA-TYPE COUPLING CONDENSER

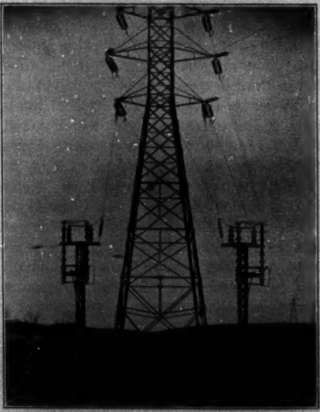

FIG. 2—COUPLING CONDENSERS ON 132-KV. LINE

Sunnyside Substation, Ohio Power Co., Canton, Ohio, one of the properties of the American Gas and Electric Co; installed on their 132,000-volt circuit between Canton, Ohio and Philo, Ohio, March 1925. This installation consists of two columns, six 22,000-volt units in series per phase.

A number of installations of this nature is at present scattered over the country, and so far the results have fully justified the theoretical considerations which have led to the choice of mica condensers in preference to other types. Some of the installations have been in continuous use for about three years, and as the carrier-wave connecting system is the link which must be as nearly trouble-proof as possible, it is interesting to note that the majority of the installations have had no trouble whatever, while in other cases the trouble has been due to lightning strokes.

**Philip Sporn:** (by letter) Mr. Belt has touched upon the question of the increased use of coupling capacitors as against coupling wires and has stressed, as a reason for that, the fact that capacitors have greater effectiveness. I should like to point out however, that while effectiveness has undoubtedly a considerable amount to do with their increasing use, there is another factor which he has failed to point out. This factor has to do with lightning and while lightning is perhaps a subject that does not give much serious trouble in California, in the East and in the Mid-west it is a subject that gives us many a sleepless night.

The work of Peek and others has shown that the ground wire is decidedly useful and very often an almost necessary part of a transmission line where lightning is much of a factor. The klydonograph work carried on by the various companies in the last two years has strengthened that viewpoint. However, whereas a ground wire is important on the line itself, it becomes doubly so at the two terminals of the line where apparatus has to be taken care of. Now what has been the practise with regard to coupling wires? In places where the line has been designed for one or two ground wires, the invariable practise has been to take the last four or five spans of the ground wire, insulate it, and use it as coupling conductor. From the standpoint of the coupling wire, this seemed the logical thing to do, but from the standpoint of the line as a whole, it was decidedly the wrong thing. The result, of course, was to give a line with a rising surge impedance at the two ends and the consequent increment in the steepness of any wave front as it approached the station. This is the reverse of the ideal aimed for, namely the decreasing impedance at the two ends. Viewed in this light, the decision between the coupling wires and coupling condensers is not very difficult. We have something like 22 carrier installations on our 132-kv. system and this involves coupling to approximately 34 different lines practically all of which are made through coupling capacitors. In the vast majority of cases the decision to go to coupling capacitors was influenced to a considerable degree by the considerations outlined above.

From the data on impulse strength of the various types outlined by Mr. Belt, it would appear that the tank type would be the most ideal capacitor. Unfortunately, however, it has the drawback that it is also the most expensive one. Looking for the next best, we find that for a given rating, the mica and oil-filled cable types have about the same impulse strength but the impulse ratios are decidedly different. It would appear therefore that the mica, if it could have 60-cycle flashover value cut down without affecting its impulse flashover, might very well compete with the cable type. In this respect, however, the general characteristics of the mica are not sufficiently well known and it would seem decidedly worth while to have more work done on the subject, particularly as in the present stage mica, from a standpoint of cost, would be decidedly the choice over cable. As regards the porcelain-type condenser (a type not discussed by Mr. Belt), this condenser utilizes materials that have been longest known and tried in the electrical circuit but in the present stage of development it certainly does not look as if it is ready to go on a system where high standards of safety are demanded. More work ought to be done on it.

**T. A. E. Belt:** Very complete tests at 60 cycles and impulse were made in order to check experimentally the electrical strength of both the cable-type and tank-type capacitors. Therefore, Mr. Stauffacher took little chance in connecting the tank-type capacitors directly to the bus at Laguna Bell and Big Creek No. 3.

Mica is a good dielectric for certain applications, but it has an objectionable characteristic which Mr. Dubilier did not bring out in his discussion; namely, the property of breaking down on steep wave fronts, such as lightning, at a lower value of potential than its maximum 60-cycle breakdown. This characteristic makes it necessary to over-insulate a coupling condenser, using mica for 60 cycles in order to have it stand up in service on a transmission line which is subjected to lightning impulse voltages. There is no measurable deterioration of an oil dielectric such as used in the cable-type and tank-type capacitors.

In general, American practise has not followed European practise, owing to the fact that operating requirements in this country are different from those in Europe and greater reliability is required.

I wish to acknowledge the help given by L. V. Bewley of the High-Voltage Bushing Department of the General Electric Company in the preparation of this paper. I also wish to state that the development of the cable-type coupling capacitor was carried out in cooperation with that department.

# The Relation Between Frequency and Spark-Over
## Voltage in a Sphere-Gap Voltmeter

BY L. E. REUKEMA[1]
Associate, A. I. E. E.

***Synopsis.****—The standard instrument for measuring crest values of high alternating voltages at 60 cycles is the sphere-gap voltmeter, which measures a voltage by the distance which it will flash between spheres. In much of the high-voltage research, however, very high frequencies are used. For measuring the voltages used in these high-frequency tests, the sphere-gap voltmeter is used, the assumption being made that its calibration at high frequency is but little, if any, different from that at 60 cycles.*

*In the endeavor to make the sphere-gap a standard for measuring peak values of voltage at high frequencies, as it is at present a standard at commercial frequencies, experimental data were obtained from which calibration curves for the sphere-gap voltmeter were plotted for frequencies ranging from 28,000 to 425,000 cycles per sec. for standard conditions of temperature and pressure. These curves cover a voltage range from about 10,000 to 50,000 volts, the source of the high-frequency voltage being a Poulsen arc with variable inductance and capacity in its a-c. circuit. The results show no appreciable change in voltage required to flash across a given gap as the frequency increases until a frequency of about 20,000 cycles is reached, then a gradual decrease in required voltage as the frequency increases from 20,000 to 60,000 cycles, after which a single curve holds for all frequencies at least up to 425,000 cycles per sec., the highest frequency tested. The theory shows that this curve should hold up to a frequency of about 6,000,000 cycles for a one-cm. gap, after which a further decrease should be found. At and above 60,000 cycles per sec., the voltage required to flash across a one-in. gap is 13 per cent lower than the voltage required at 60 cycles, provided only the ions occurring naturally in the atmosphere are available to start the ionization which produces the flashover.*

*In the course of the investigation it was noted that flooding the spheres with ultraviolet light decreased the voltage required to flash across a given gap at high frequency by about 3.5 per cent, whereas no such effect is found at commercial frequencies. Therefore a complete set of calibration curves for the frequency range covered was also obtained for the spheres flooded with ultraviolet light.*

*The results are explained by showing that at high frequency a space charge of positive ions will accumulate between the spheres, this space charge distorting the potential gradient sufficiently to allow a spark to pass, even though the average gradient between spheres is considerably lower than is necessary at 60 cycles. The space charge depends on the rate at which ions are added to the field by ionization and the rate at which they are lost by diffusion and mutual repulsion, the terminal condition reached when the rate of gain equals the rate of loss determining the voltage at which flashover will take place at any given frequency.*

ONE of the prime requisites in all high-voltage research is to be able to measure accurately the voltages employed, and, since it is the peak value of the voltage wave which ruptures insulation, it is especially important to be able to determine this peak value. For such measurements at commercial frequencies, that is, 25 to 60 cycles, the sphere-gap voltmeter, which measures a voltage by the distance which it will flash between spheres, is now the standard instrument. For much of the research in high-voltage phenomena, however, very high-frequency power is used. In much of the insulation testing, for instance, the sources of power are impulse oscillators generating voltages up to 1,500,000 volts or more at frequencies ranging from 30,000 to 500,000 cycles. The sphere-gap voltmeter is the accepted means of measuring such voltages, the assumption being made that the calibration of the instrument is little, if any, different at high frequency from that at 60 cycles. To test the correctness of this assumption was the first object of this research.

In the course of taking the experimental data to determine the relation of frequency to spark-over voltage between spheres, an interesting and important fact was noted, namely, that exposing the spheres to the action of ultraviolet light has a very pronounced effect on the voltage necessary to flash across a given gap. At 60 cycles, the action of ultraviolet light on the spheres is merely to increase the accuracy of the sphere-gap as a voltmeter, but the average voltage required to spark across a gap is neither increased nor decreased to a noticeable extent. At high frequencies, however, a pronounced lowering of the voltage required for a given gap manifests itself whenever a source of ultraviolet light plays upon the spheres. The investigation of this phenomenon, discovered many years ago by Hertz, but apparently overlooked by engineers, constituted the second object of our research.

In any investigation of physical phenomena, the value of the experimental data is considerably enhanced if a rational explanation of the results accompanies them. Such an explanation, on the basis of the fundamental physical principles known concerning electrical discharges through gases, together with an attempt to correlate the newly discovered phenomena with already existing knowledge on the subject, is the third object of the research.

### Previous Investigations

The first object of this investigation is not a new problem, as several of the recognized leaders in the development of our knowledge of electrical phenomena have contributed toward its solution. A brief summary of the conclusions reached by former investigators will serve as a fitting introduction to the present investigation.

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*Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., Sept. 13-16, 1927.*

In 1911, J. B. Whitehead and W. S. Gorton started an extensive investigation of the electric strength of air, publishing their results serially in the A. I. E. E. JOURNAL. In one of these papers[2] they state: "There seems, however, to be no doubt that there is a decrease in corona voltage, amounting to about 3 or 4 per cent, in increasing the frequency from 60 cycles to 2000 cycles or over."

L. W. Chubb and C. Fortescue in 1913 investigated the effect of frequency on the spark-over voltage between spheres over the range from 25 to 60 cycles, and found frequency to have no effect in this range.

On June 24, 1914, at the A. I. E. E. convention at Detroit, F. W. Peek, jr., who is responsible for most of the research on the sphere-gap voltmeter, discussed the effect of frequency on spark-over voltage between spheres as one of a number of related investigations carried on, at the General Electric high-tension laboratory, under his direction. He compared a 1000-cycle curve with a 60-cycle curve and found no difference with spark-over voltage plotted as a function of the gap. A 40,000-cycle curve, however, lies below the 60-cycle curve for its entire length, the percentage differences increasing as the voltage increases, from about 11 per cent at 11,000 volts to 16 per cent at 25,000 volts, high frequency. This curve contains only ten points, however, two of them over 10 per cent off of the curve. Moreover, if two points lying below the curve are assumed to be the only ones greatly in error and are disregarded, a smooth curve could be drawn through the remaining points which would raise the curve about 5 per cent. Therefore, this curve could hardly be regarded as conclusive. Moreover, Peek himself does not so consider it. He attributes the decrease in required voltage at high frequency to rough spots on the spheres, as no special care was taken to polish them. In his book, "Dielectric Phenomena in High-Voltage Engineering," 1920 Edition, Peek states: "It seems that the air at high frequency of the above order (40,000 cycles) is only apparently of less strength. If the sphere surfaces are highly polished, it seems that the high-frequency spark-over voltage should check closely with the sixty-cycle voltage. This should also apply for corona on polished wires. The following limitation, however, applies to both cases. At continuous high frequency when the rate of energy or power is great, frequency may enter the energy-distance equation thus

$$A \sqrt{\frac{r}{\delta}\,\varphi(f)}$$

and spark-over take place at lower voltages at very high frequency."

At this same convention, Professors Harris J. Ryan and J. Cameron Clark of Stanford University reported the results of an investigation which they had conducted on the relation of frequency to spark-over voltage, presenting curves of voltage as a function of spark-over distance at three frequencies, 123,000 cycles, 255,000 cycles, and 612,500 cycles. Ryan and Clark drew a single curve through the mean of all points, compared this curve with a 25-cycle curve located by Fortescue and Chubb, and found their own curve to lie almost uniformly 4500 volts below the 25-cycle curve, at least within the range from 20,000 to 50,000 volts. Ryan and Clark used seven-in. spheres, however, while Chubb and Fortescue used spheres 25, 37.5, and 50 cm. in diameter. To determine whether this difference in voltage might possibly be due to a difference in the size of the spheres used, the writer compared the curve of Ryan and Clark, changed to standard conditions of temperature and pressure, with a curve for seven-in. spheres calculated from Peek's formula for spark-over voltage for spheres of any size. In this comparison, the high-frequency curve veers away from the 60-cycle curve more gradually, but at about 50,000 volts the high-frequency curve lies 6500 volts or about 13 per cent below the 60-cycle curve.

Alexanderson also investigated the problem to a slight extent in 1914 with his 100,000-cycle sine-wave alternator, and found that a three-in. gap between five-in. spheres breaks down at about 100,000 volts. He does not definitely state that the high frequency used was 100,000 cycles, nor does he say whether or not one of the spheres was grounded. If it was grounded, as is probable, this shows about a 14-per cent lowering of required voltage at high frequency. Alexanderson used highly polished spheres.

Since the amount of data on the relation of frequency to spark-over voltage by all experimenters combined is rather meager and some of it conflicting, the present investigation was conducted in the hope of clearing up the question, and thus making the sphere-gap a standard means of measuring high-frequency voltages, as it is at present a standard for 60 cycles.

Concerning the second object of the research, the investigation of the effect at high frequency of flooding the spheres with ultraviolet light, literature on the general subject has nothing to say. Apparently this phenomenon has, until our discovery, escaped the notice of both physicists and engineers. Also, so far as we have been able to determine, no one of the previous investigators has tried to show, from fundamental principles, why the required voltage at high frequency should be lower than at 60 cycles.

## THE PRESENT INVESTIGATION

The generation of voltages ranging up to 50,000 volts at frequencies of 60 to 500 cycles presented no difficulty, as generators and transformers for these frequencies were available. A diagram of the set-up for the tests is shown in Fig. 1. For the higher frequencies, a two-kw. Poulsen arc, generously loaned to us by the Federal Telegraph Co., was the source of power. For the a-c. circuit of the arc, we constructed a large air condenser and 24 inductance coils, of open design so as to withstand the high voltages induced, and with a minimum ratio of resistance to inductance, so as to obtain a maximum induced voltage. The inductance coils and the condenser are connected in series across the arc, the leading reactance of the condenser neutralizing the lagging reactance of the inductance coils, so that only the high-frequency resistance of the circuit limits the flow of current. The voltage built up across the coils and that across the condenser neutralize each other, so that either one may be over a hundred times as large as the d-c. voltage impressed across the arc. The high voltage between the condenser plates is impressed across the sphere-gap voltmeter. By varying the distance between the condenser plates and the number of inductance coils used, the frequency may be varied over a range from 28,000 cycles to about 450,000 cycles per sec. according to the formula

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[2] The Electric Strength of Air.-V The Influence of Frequency, A. I. E. E. TRANSACTIONS, Vol. XXXIII, 1914, p. 969.

$$f = \frac{1}{2\,\pi\,\sqrt{L\,C}}$$

where $f$ is frequency in cycles per sec., $L$ is inductance in henrys, and $C$ is capacity in farads.

To measure the voltage impressed between the spheres, three condensers in series to break up the voltage were used, a gold-leaf electroscope reading the voltage drop across the middle condenser. The electroscope reads effective values of voltage, whereas it is peak value which causes a flashover; therefore the wave forms of the low-frequency voltages, over the entire range of voltages used, were photographed with an oscillograph and the oscillograms analyzed mathematically to determine the ratios of effective to maximum voltages for this range. The voltage waves from the Poulsen arc were investigated with a sensitive wavemeter, and all harmonics found to be negligible, so that they may be assumed to be pure sine waves within a very small fraction of one per cent.

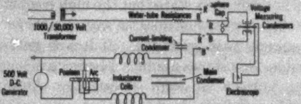

FIG. 1—DIAGRAM OF CONNECTIONS FOR CALIBRATING SPHERE GAP AT HIGH FREQUENCY AND HIGH VOLTAGE

## DESCRIPTION OF APPARATUS

The sphere-gap voltmeter was constructed according to A. I. E. E. specifications. The spheres are of brass, 6.25 cm. in diameter and accurately turned. The lower sphere is movable in a vertical direction, and the gap may be readily read to a thousandth of an inch. Neither sphere was grounded.

Since the high-frequency voltage obtainable from a Poulsen arc equals $\frac{E}{R}\sqrt{\frac{L}{C}}$, in which $E$ is the voltage across the a-c. terminals of the arc, $R$ is the resistance of the a-c. circuit, $L$ is the inductance of the coils, and $C$ is the capacity of the condenser, a high ratio of inductance to resistance is necessary in the coils in order to induce the large voltages desired. The resistance of the coils at high frequency is many times that at 60 cycles, due to both skin effect and to eddy-current loss in the copper caused by the magnetic flux of the coil cutting the turns. The coils used were designed to make this high-frequency resistance a minimum, using formulas developed by C. L. Fortescue and published in the Sept., 1923 issue of the *Journal of the British Institution of Electrical Engineers.* Twenty-four coils were constructed, 30 in. in outer diameter and 12 in. in inner diameter, containing eight layers of three turns each, turns being mounted on wooden pegs and spaced one in. apart. The smallest high-frequency resistance for this size of coil is obtained by using No. 9 B & S gage wire.

The principal considerations in the design of the condensers used in series with the inductance coils were to keep the energy losses down to a minimum and to prevent the formation of corona. Energy losses increase the effective resistance of the circuit and therefore decrease the voltage obtainable. Corona, in addition to wasting energy, introduces a source of error into the sphere-gap readings by setting up minor surges in the circuit, which may cause flashovers between the spheres even though the fundamental voltage which is being measured may be much too low. These considerations, together with the high voltages used, called for large condenser plates separated sufficiently by air to prevent flashes between them, and free from sudden bends, sharp corners, and irregularities of any kind. The plates used measured seven by eight ft. and were constructed of galvanized iron nailed to wooden frames, with quarters of copper float balls soldered to the four corners and with metal connectors soldered to the sides to receive the connections from the inductance coils. To prevent stray electrostatic flux from these condenser plates from spreading out into the voltage-measuring apparatus, grounded shields of fine-mesh chicken wire, stretched on pipe frames, were hung on both sides of the condenser.

In parallel with the sphere-gap were three air condensers in series, the middle one of the three having a much larger capacity than that of the two outer ones. These condensers divide the voltage between them in inverse ratio to their capacities, so that the voltage drop across the middle one was about two per cent of the total voltage impressed across the sphere-gap. This voltage drop across the middle condenser was measured by means of a gold-leaf electroscope, connected in parallel with the condenser. The plates of all of the condensers are of galvanized iron on wooden frames supported in vertical planes, and are free from sharp edges and rough spots, with joints covered with tinfoil to prevent the formation of corona, since it is essential for accurate work that the losses in the condensers be negligible at all frequencies. The plates of the middle condenser are five ft. sq. and one in. and a half thick, are suspended from insulated supports, and are separated about three-eighths of an in. by small porcelain insulators. Each of the outer condensers consists of an outer plate two ft. sq. and one in. and a half thick, which fits inside a boxlike plate, with a bottom three ft. sq. and sides one ft. high, the plates being separated about five in. The smaller plates are connected to the voltage to be measured. Each of the boxlike plates is connected to the adjacent plate of the inner condenser, the boxes facing away from each other. In this way the electrostatic flux from one outer plate is prevented from reaching the other, and also from setting up a stray field in the vicinity of either the sphere-gap or the electroscope. Each condenser is insulated from ground by small porcelain insulators.

The electroscope consists of a nickeled steel case with glass front and back, down the center of which extends a nickeled brass rod carrying the gold leaf. To prevent possible external flux from penetrating the interior of the electroscope, the glass front and back were threaded both horizontally and vertically with fine wires. The rod bearing the gold leaf is insulated from the case by sulphur. A protractor was arranged to turn on an axis in line with the point of connection of the gold leaf, a line peep-sight directly in front of the protractor and a frame carrying a fine hair about four in. behind the protractor turning with the latter as an integral part. This makes it possible to read the deflections of the gold leaf to the tenth of a degree, which compares favorably with the accuracy of the sphere-gap itself.

Whenever a spark takes place between the spheres, a short circuit is produced across the transformer in the case of the low frequency and across the Poulsen arc in the case of the high frequency. To prevent the burning and pitting of the spheres which would otherwise result from such short circuits, water-tube resistances were placed in both high-tension legs of the transformer circuit, and a one-$\mu$ f. condenser successfully limited the flow of current from the high-frequency circuit. The voltage drops in the water-tube resistances and in the current-limiting condenser occurred before the voltage was impressed on the sphere-gap and measuring condensers and therefore were in no sense a source of error in the measurements.

The source of ultraviolet light with which the spheres were flooded was an open arc light, ordinarily used for oscillographic work, which was placed about four ft. from the spheres with the light concentrated on them.

## PROCEDURE

As the sphere-gap voltmeter is a standard instrument for the measurement of high voltage at 60 cycles, the electroscope was calibrated by reading its deflections for spark-overs between the spheres for voltages ranging from about 7000 to 55,000 volts effective, the voltage being varied by varying the field of the alternator. Since the object of the research is to compare the high-frequency voltage corresponding to a given gap with that required at 60 cycles, this method eliminated the errors which would have crept in if the electroscope had been calibrated with direct current and the capacities of the condensers measured. The readings of the sphere-gap were reduced to standard conditions, 760-mm. pressure and 25 deg. cent., as adopted by the A. I. E. E., and were also corrected for wave form, since the sphere-gap measures crest values and the electroscope effective values of voltage. Although the generator supplying the 60-cycle power produced a practically pure sine wave, the voltage drops within the transformers due to the harmonics of the exciting currents and the distortion due to the internal capacity of the 50,000-volt transformer produced a slight change in wave form, which necessitated the mathematical analysis of the voltage wave on the high-tension side of the transformer, for the range of voltages used in the test. Oscillograms of these waves at six representative values of voltage were analyzed, and the ratio of maximum to effective value of the actual waves compared to this ratio for a pure sine wave. The corrective value averaged about 0.8 per cent and in no case was larger than 1.8 per cent.

The electroscope and measuring condensers having been calibrated for a given setting of the condensers, high-frequency runs were taken, reading electroscope deflections as a function of distances between spheres for the maximum range of voltages obtainable at any one frequency. Temperatures and barometric pressures were recorded, so that the gap readings might later be reduced to those for standard conditions. The voltages were varied by changing the d-c. voltage impressed on the Poulsen arc, the length of the arc-gap, and the strength of the magnetic deflecting field so as to give steady operation. Frequencies were varied by changing the number of inductance coils used and the distance between the main condenser plates. Frequencies were calculated from the wavelength readings of a wavemeter. Runs averaging approximately 100 readings each were taken for frequencies ranging from 28,170 to 425,500 cycles, both with the spheres flooded with ultraviolet light and without. Runs at 133 cycles, 250 cycles, and 500 cycles were also compared with those for 60 cycles. In order to be sure that the particular setting of the measuring condensers was not a source of error, runs were taken for several different settings, each setting requiring a separate electroscope calibration. The surfaces of the spheres were kept highly polished at all times, by polishing them with a power buffer at least once and usually several times during each run, and by hand with a soft towel after each spark-over.

To obtain a reading, the distance between spheres was made slightly greater than could be flashed across by the voltage impressed, then the spheres were slowly moved together by turning the control wheel until the spark occurred, at the same time keeping the peep-sight of the protractor arrangement trained on the deflected gold leaf, so that the voltage at the instant of flashover could be read accurately. The spheres were always moved together at least a full turn of the control wheel before a flash took place, so as to avoid any error due to lost motion in the control wheel. In case the voltage at the instant of flashover was unsteady, the reading was thrown out. Care was taken to bring the voltage from the Poulsen arc up to the maximum possible with the d-c. voltage impressed before taking a reading, so as to eliminate errors due to surges.

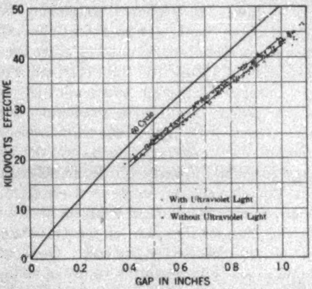

Fig. 2—Calibration of 6.25-cm. Spheres at 95,540 Cycles

## Data and Curves

The publishing of the 50 pages of data secured would serve no useful purpose, since the curves show the results obtained. Moreover, of the many pages of curves plotted, only three are included in this paper. Fig. 2 is included to show approximately the accuracy with which the points fall on the various curves, and the very evident difference between the voltage necessary to flash across a given gap when the spheres are flooded with ultraviolet light and when they are not. The fact that all points do not fall accurately on the curve when ultraviolet light is flooding the spheres is due to a slight unsteadiness which is inherent in the Poulsen arc, not to any inaccuracy of the sphere-gap itself. Using ultraviolet light, 60-cycle curves always repeat themselves accurately, no point falling more than a quarter per cent off the curve. When ultraviolet light is not used, any point may be as much as two per cent off the curve.

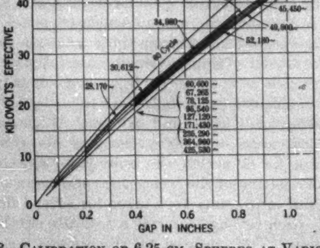

Fig. 3—Calibration of 6.25-cm. Spheres at Various Frequencies Using Ultraviolet Light

Figs. 3 and 4 show the final results of the test, the one when the spheres are flooded with ultraviolet light, the other when the spheres are not so flooded.

## Theoretical Explanation of the Results

*Mechanism of the Spark.* Before considering the phenomena of electric discharge through gases, it may be advisable to recall certain fundamental concepts of the constitution of matter. All matter is composed of molecules in continuous motion, the temperature of any substance being merely a function of the energy of motion of its molecules. In a gas, such as our atmosphere, the molecules are relatively far apart, and the continual collisions of molecules with each other and with the walls of the containing vessel give rise to the pressure of the gas. The average distance traveled by a molecule before colliding with another molecule is known as its mean free path. All molecules, in turn, are composed of atoms, different combinations of the 92 kinds of atoms producing the millions of varieties of molecules. The atoms are composed of a central nucleus with a positive electric charge and of particles of negative electricity, called electrons, which travel around the nucleus in precessing elliptic or circular orbits at enormously high speeds, the electrical attraction of the positive nucleus for the negative electrons balancing the centrifugal force produced by these speeds. An atom thus may be compared to a solar system, its volume being mostly empty space. The number of planetary electrons in a neutral atom is always equal to the number of equivalent positive charges of the nucleus.

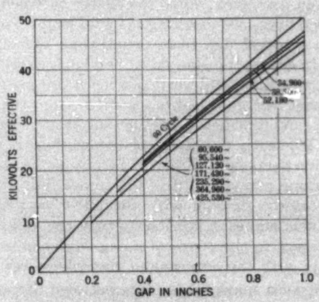

Fig. 4—Calibration of 6.25-cm. Spheres without Ultraviolet Light

It is possible for an atom to lose an electron, however, in which case it is called a positive ion, since the loss of a particle of negative electricity leaves the rest of the atom positively charged. Similarly, a free electron is able to attach itself to most atoms. When this happens, the atom with its extra electron is called a negative ion. An ion, whether positive or negative, behaves like an ordinary molecule, as long as it is not in an electric field. As soon as an electric field is produced, however, the ion adds to its haphazard molecular motion a motion in the direction of the field, toward the positive electrode if a negative ion, toward the negative electrode if a positive ion. If this motion takes place in a vacuum, so that the mean free path of the ion is large, a comparatively small voltage drop, about 16 volts for air, is sufficient to give the ion such a high velocity that it is able to knock an electron out of a molecule with which it collides. This potential is known as the ionizing potential of the molecule, that is, the potential necessary to knock out one of its electrons and thus make an ion of it. As the pressure of the gas increases, however, the mean free path decreases until at atmospheric pressure the air molecule has a mean free path of only about 0.000004 in. In such a short distance it does not have the chance to acquire the ionizing speed except at very high potential gradients.

Whenever a molecule is ionized, the electron which is knocked out of it also feels the force of any electric field in which it finds itself. As an electron weighs only about one sixty-thousandth part as much as an oxygen molecule, however, and since the acceleration which an object undergoes in a given field is inversely proportional to the square root of its mass, its acceleration is evidently about 240 times that of an ionized oxygen molecule. Moreover, due to its increased speed and its much smaller size, its mean free path is four times the square root of two or 5.66 times that of the molecule. The electron, therefore, will attain a velocity many hundreds of times that attained by an ion in the same field. Moreover, because of its smaller weight, as compared with that of a molecule, the electron cannot lose more than a small fraction of its energy in an ordinary collision with a molecule. Thus it gradually accumulates velocity until the average amount it loses per collision equals that gained between collisions, the terminal velocity being a function of $\frac{E}{d}$, where $E$ is potential gradient and $d$ is density of the air. If the amount of energy represented by this terminal velocity is as great or greater than the energy necessary to ionize a molecule, such an ionization may take place, the probability of the ionization increasing rapidly with increase in velocity, up to velocities far beyond any which would be given the electron in air by an electric field.

Now let us consider the mechanism of the electric spark between two electrodes with a potential gradient between them. Even though this potential gradient is far greater than that necessary to ionize the air molecules, no spark will take place unless there are either ions or electrons present to start the ionization. A few ions per cubic centimeter are practically always present in the air, however, and new ones are being formed, mainly by the action of the penetrating radiation recently investigated by Millikan and by radioactivity, at the rate of about 12 per sec. per cu. cm. The electron starts to ionize at a considerably smaller potential gradient than does the ion, and even though it ionizes only once for every thousand collisions, an electron would increase to approximately 485,000,000 in moving one cm. For instance, the mean free path of the electron in air at atmospheric pressure is about 0.00005 cm. If it ionizes once in a thousand collisions, it would ionize about 20 times per cm. The rate of increase in the number of electrons, due to ionization by electrons alone, is given by the equation

$$n = n_0 \, e^{ax}$$

where $n$ is the number of electrons after the initial electrons have moved a distance $x$ in the direction of the force, $n_0$ is the number of electrons at $x = 0$, $a$ is the number of ionizations per centimeter, and $e$ is equal to 2.71828, the base of the Napierian logarithm. Since in our assumption $a$ equals twenty, $n$ equals one, and $x$ equals one,

$$n = e^{20} = 485{,}122{,}000$$

However, one coulomb of electricity equals 6,280,000,000,000,000,000 electrons, so that this enormous number of electrons would have to be formed per second to have just one ampere of current pass. Moreover, as fast as these electrons are produced by ionization, they are swept into the positive electrode, leaving only the small number spontaneously formed by radiation or by radioactivity to carry on the work. Evidently, therefore, ionization by electrons alone will not produce a spark.

For each electron set free by collision, however, there is also produced a positive ion, which is attracted in the opposite direction from that taken by the electrons. If the potential gradient is sufficient to allow positive ions to ionize air molecules by collision, or to knock electrons out of the negative sphere, the number of electrons produced, immediately increases enormously. Suppose that only one in a thousand of the positive ions produced was able to ionize and that this ionization took place close to the negative electrode, where the potential gradient would be greatest. Then one electron, with the help of the electrons which it sets free by collision, produces 485,000,000 positive ions while moving one cm. Of these positive ions, 485,000, each ionizing once, then produce 485,000 new electrons, which, starting close to the negative electrode, each produce 485,000,000 positive ions in moving one cm., or a total of 235,000,000,000,000. One one-thousandths of these, or 235,000,000,000, produce

235,000,000,000 more electrons close to the negative electrode, which in turn produce 485,000,000 times 235,000,000,000 electrons, and so on, all of this happening in a very small fraction of a second. The process is thus cumulative, the number of ions and electrons increasing at an enormous rate, and resulting in a flashover between the electrodes. Note that ionization by both electrons and positive ions is essential, and that, since the electron ionizes at a lower potential gradient than does the positive ion, the probability of ionization by the latter is the factor which determines the potential gradient necessary to produce a spark between the electrodes. This potential gradient has been found to be 30,000 volts per cm. under standard conditions of temperature and pressure.

The reason for the increased accuracy of the sphere-gap at low frequencies when ultraviolet light shines on the spheres is now easily understood. The action of the ultraviolet light is to liberate electrons from the spheres, a phenomenon which has been named the photoelectric effect. Thus, when the spheres are flooded with ultraviolet light, there is always a large number of electrons in the space between the spheres to start the ionization, and the instant the potential gradient reaches a value of 30,000 volts per cm., a spark takes place. When, on the other hand, the small number of ions found naturally in the air must be depended upon to start the ionization, there may be no ions available at the instant the potential gradient reaches the required value. This is especially true in the sphere-gap voltmeter, in which the potential gradient gradually increases as the spheres are moved together. The gradient, before it has reached the value required for ionization by collision, simply sweeps into the spheres whatever ions are present, so that when the potential gradient does reach 30,000 volts per cm., the diffusion, into the space between electrodes, of ions from the outer space must be depended upon to start the ionization. This may take an appreciable part of a second or even more, during which time the spheres are being moved closer together, with the result that a higher potential gradient seems to be required to flash across the gap than actually is required. Thus, the determination of a voltage by means of a sphere-gap voltmeter, which is not subject to the action of ultraviolet light, may be one or two per cent in error.

## EFFECT OF HIGH FREQUENCY

To understand the effect of high frequency on the voltage required to spark across a given gap, we must consider such phenomena as the mobility of ions, their diffusion, and the variation of potential gradient by space charge. The effect of the attachment of electrons to molecules and the recombination of electrons with positive ions to form neutral molecules is negligible in the high electric fields used. The mobility of an ion is the velocity with which it moves in an electric field. The mobility constant is the velocity in centimeters per second attained by an ion, at 760-mm. pressure and 0 deg. cent., per volt per centimeter of field acting upon it. This constant for positive ions in air is 1.32; for negative ions, 1.8. In high fields, the mobility is nearly independent of temperature, so that the error would be small if one neglected to correct gas ion mobilities for temperatures above 200 deg. $K$. The mobility of *electrons* does not vary directly with potential gradient, so that for electrons there is really no such thing as a mobility constant. The mobility is a function of $\frac{E}{p}$, however, where $E$ is potential gradient in volts per cm. and $p$ is pressure. According to a curve for electron mobility in nitrogen in a paper by Compton in the *Physical Review* of 1923, an electron in nitrogen at atmospheric pressure would attain a velocity of 13,800,000 cm. per sec. under the action of a potential gradient of 30,000 volts per cm., or it would be swept across a gap of one cm. in $\frac{1}{13{,}800{,}000}$ sec. For air, instead of nitrogen, the figures would not differ greatly. A positive ion, under the same conditions in air, would attain a velocity of 30,000 times 1.32 or 39,600 cm. per sec. If the field were an alternating one, the velocity would vary as the voltage varied. For a pure sine wave of 30,000 volts per cm. effective value, the distance traveled by an electron in one sec. in the direction of the force would be 12,160,000 cm.; by a positive ion, 35,650 cm. Evidently at 60 cycles both ions and electrons would practically all be swept out of the field every half-cycle, so that until the potential gradient has reached 30,000 volts per cm., there could be no appreciable accumulation of space charge to distort the field.

Consider the same phenomena at high frequency, let us say at 50,000 cycles per sec. The electrons are practically all swept into the spheres every half-cycle, just as at 60 cycles. The positive ions have time to move, however, for a gradient of 30,000 volts per cm. only about 0.35 cm. during a half-cycle, so that there is a rapid accumulation of positive ions in the space between the spheres, these ions simply surging back and forth between the spheres as the potential gradient reverses every half-cycle.

Consider the effect of this positive space charge on the distribution of the total voltage between the spheres. If there were no space charge, the electrostatic flux lines would all extend from the positive to the negative sphere, and although the potential gradient would be lower halfway between the spheres than it would be close to the sphere surface due to the spreading out of the flux lines, the distribution of the potential gradient would be symmetrical with respect to the spheres. When a positive space charge is present, however, the flux lines do not all extend from the positive to the negative sphere. All of them end on the negative sphere, but many of them extend out to the positive ions in the space between the spheres, instead of to the positive sphere. Since the potential gradient is proportional to the density of the electrostatic flux lines, it follows that the potential gradient between spheres is distorted, constantly increasing as the negative sphere is approached, or at least being greater near the negative sphere than it would be if the positive space charge were not present. Therefore, even though the total voltage would otherwise not be able to cause positive ionization, this distortion of the field increases the potential gradient close to the negative sphere sufficiently to allow the positive ions to ionize there, where their ionization is most effective in producing a consequent large number of electrons by electron collision as the electrons produced by the positive ions move to the positive sphere. The voltage required to spark across a given gap, therefore, should be less at high frequency than at 60 cycles, because of the distortion of the potential gradient by the positive space charge.

Let us see how large the effect of this positive space charge may be. Consider two spheres, 6.25 cm. in diameter, one cm. apart, with a potential gradient of 30,000 volts per cm. at the surface of each sphere along the line joining their centers. The electric charge per square millimeter of such surface would be $0.0265 \times 10^{-9}$ coulombs to give this gradient at the surface, which is equivalent to $0.0265 \times 10^{-9} \times 6.28 \times 10^{18}$ or 166,400,000 excess electrons on one sphere per square millimeter of surface, and an equal deficiency on the other sphere. To appreciably distort the potential gradient along the line connecting the spheres, it is therefore necessary that the space charge, within a column one mm. square joining the spheres, be an appreciable fraction of 166,400,000 ions. If the space charge amounted to the full 166,400,000 ions per sq. mm. column, all of the flux lines leaving the negative sphere would end on ions in the space, and the gradient at the positive sphere would be zero. If the distribution of ions were uniform in such a case, the potential gradient at the negative sphere would be approximately twice the average gradient. Actually the distribution is not uniform, but the ions are concentrated mainly near the spheres, as is evident when one consideres their method of production. The potential gradient would then change rapidly in the vicinity of the spheres, but the maximum gradient would still be approximately twice the average gradient. If the space charge amounted to 20 per cent of this 166,400,000 ions per sq. mm. column, the maximum gradient would be increased about 10 per cent. This increase would hold for a 20 per cent space charge, regardless of the distribution of the space charge, as long as the distribution was symmetrical with respect to the spheres, as it would very nearly be for high-frequency voltage impressed across the gap. To produce at high frequency a 14 per cent increase in the maximum potential gradient as compared with the maximum potential gradient corresponding to a total voltage between spheres at 60 cycles would require about 37,000,000 ions of space charge per sq. mm. column one cm. long connecting the spheres along their line of centers. When one considers that a single electron, ionizing 20 times in traveling one cm., is responsible, with the aid of the electrons it sets free, for the production of 485,000,000 positive ions, it is evident that a space charge of 37,000,000 ions per sq. mm. column per cm. is not only possible, but may be formed in a very small fraction of a second, provided the positive ions are not swept into the negative sphere as soon as formed, as is the case at 60 cycles, but are held in the field, merely oscillating slightly about positions of equilibrium, as is true at high frequency. This explains why a smaller voltage is required to produce a spark across a given gap at high frequency than at 60 cycles.

Let us now consider the effect on the space charge, and therefore on the voltage for a given gap, of gradually increasing the frequency. At 30,000 volts per cm. effective value, we have found that the average velocity of the electron over a half-cycle is 12,160,000 cm. per sec. Therefore an electron could get across a one-cm. gap up to a frequency of about 6,000,000 cycles. The corresponding velocity of the positive ion is 35,650 cm. per sec. Therefore a positive ion could be held oscillating between spheres for a frequency as low as 18,000 cycles, provided it were formed at just the right part of the cycle. At such a frequency, however, only a small percentage of the positive ions formed would be held in the space between spheres, the rest being sucked into the spheres. Therefore only a small space charge would accumulate, and the voltage necessary to produce a spark would be very little less than that required at 60 cycles. As the frequency increases, the distance the positive ions move in a half-cycle decreases, until at 60,000 cycles this distance is only 0.297 cm. for a potential gradient of 30,000 volts per cm., and correspondingly less for any smaller gradient. Note how many ions are now held in the field. If an electron, on the average, ionizes 20 times in traveling one cm. in the direction of the field, $\left(1 - \frac{1}{e}\right)$ or 63.2 per cent of the positive ions, when the first stream of electrons is sucked out of the gas, are within a twentieth of a cm. of the positive sphere; $\left(1 - \frac{1}{e^2}\right)$ or 86.4 per cent are within two-twentieths; 95.02 per cent, within three-twentieths; 98.77 per cent, within four-twentieths, etc. At the end of the first cycle, however, all of these ions have moved away from this sphere a distance of 0.297 cm. for a 30,000-volt gradient, and, except for the effect of diffusion, these ions cannot be captured by the spheres. If we assume that half of the maximum voltage of the cycle is necessary to allow the electrons to ionize appreciably, so that the first appreciable ionization occurs when one-sixth of the half-cycle is completed, all of the first ions formed which were produced within $\frac{0.297}{6}$ or 0.05 cm. of the positive sphere will be sucked into the sphere during the following half-cycle. This leaves 36.8 per cent of the ions to accumulate for the space charge, since the assumption that the electrons ionize 20 times per cm. means the production of $\left(1 - \frac{1}{e}\right)$ or 64.2 per cent of the ions within 0.05 cm. of the positive sphere. Of the ions formed at the first third of the half-cycle, 13.53 per cent accumulate for the space charge; of those formed 30 deg. later, 4.98 per cent accumulate, etc. Thus approximately 10 per cent of all the ions formed are held for the space charge, neglecting the effect of diffusion.

This effect, however, is not negligible, since the rate at which the ions are lost by diffusion increases with the concentration of the ions. The number lost by diffusion is given by the formula

$$N = D \frac{d\,n}{d\,z} d\,x\,d\,y$$

where $N$ is the number diffusing per second across the area $d\,x\,d\,y$ when the space rate of change in the concentration in the $z$ direction is $\frac{d\,n}{d\,z}$, and $D$, the diffusion constant, equals 0.028 for positive ions in dry air and 0.032 in moist air. Since $\frac{d\,n}{d\,z}$ for large ion concentration may be many millions, the number of ions lost by diffusion is far from negligible, and, since the number of ions formed per second is practically independent of ion concentration, and the number lost by diffusion increases with increase in concentration, evidently a terminal condition will be reached when the rate of ion loss equals the rate of gain. This terminal condition determines what space charge will be accumulated, and therefore how much the potential gradient will be distorted.

Since the terminal condition depends on the rate of ion gain, it is at once evident that a lower voltage should be required at high frequency when the action of ultraviolet light provides an ample supply of electrons in the gap to start the ionization than is required when the number of electrons is limited to those naturally at hand. The decrease in the required voltage as the frequency increases is also easily understood, since the higher the frequency the larger is the percentage of ions which are retained in the gap, and therefore the larger is the rate of ion gain. But above a frequency of 60,000 cycles, we find that the voltage required to flash across a given gap no longer decreases with an increase in frequency. To understand this, we must consider the distribution of ions in the gap at different frequencies The distribution is always symmetrical with respect to the spheres. At the lowest frequencies at which it is possible for a space charge to accumulate, the distribution throughout the gap is fairly uniform, since the ions can move almost across the gap in a half-cycle. As the frequency increases, the ions tend more and more to concentrate close to the surfaces of the spheres, since this is the position in which most of them are produced and the time allowed for them to move away is inversely proportional to the frequency. This concentration near the sphere surfaces, of course, increases the loss of ions by diffusion, and at some frequency this increased loss of ions must neutralize the increased rate of production. Our data show that this frequency is about 60,000 cycles per sec., both when the spheres are subject to the action of ultraviolet light and when they are not. That the action of ultraviolet light should not change this limiting frequency is predictable from our theory, since the effect of concentration of ions near the sphere surface in increasing diffusion depends merely on the frequency, not on the rate of ion production.

## COMPARISON OF PRESENT RESULTS WITH THOSE OF PREVIOUS INVESTIGATORS

Since other investigators used spheres of various sizes and the voltage necessary to flash across a gap depends on the size of the spheres, actual voltages for a given gap will not check. The percentage variation of the high-frequency curves from the 60 cycle curves should be substantially the same for spheres of all sizes, however, and the results of other men should at least approximately check our own, provided all results compared are fairly correct. The data of Ryan and Clark were taken for 123,000, 255,000, and 612,500 cycles, a single curve being drawn through all of the points. This curve, changed to standard conditions and plotted on the same sheet with a 60-cycle curve, calculated for seven-in. spheres, may be compared with our own results. For a one-in. gap, their high-frequency curve lies 13 per cent below the 60-cycle curve; for the same gap our curve lies 12.8 per cent below, a very close check. A comparison with Peek's 40,000-cycle curve shows his high-frequency curve to lie considerably lower than our own. Peek's own conclusion, however, is that its extreme lowness is due to rough spots on the spheres, as no special care was taken to polish them. The comparison with Alexanderson's results can be qualitative only, since he gives results only for 100,000 volts, a higher voltage than we used. Also he does not definitely state the frequency used, although the text would seem to indicate that it was in the vicinity of 100,000 cycles. Moreover, he does not state whether or not one sphere was grounded. If one sphere was grounded, as it probably was, his high-frequency curve lies about 14 per cent below the 60-cycle curve, which agrees very well with our results. Alexanderon's spheres were highly polished. No results for tests at frequencies between 60 and 500 cycles have been published. The fact that our curves for 60, 133, 250, and 500 cycles all coincide, however, as theory says they should, leaves little doubt as to the accuracy of these curves. The close agreement of the results of Ryan and Clark and of Alexanderson with our own for the few frequencies tested by these investigators gives us confidence in the reliability of our other curves for which no comparison with previous investigations is possible.

## CONCLUSION

The effect of high frequency is to decrease the voltage necessary to flash across a given gap between spheres. This effect starts at about 20,000 cycles, and increases up to about 60,000 cycles, after which there is no further change.

At and above 60,000 cycles, the voltage required to spark across a one-in. gap is about 13 per cent lower than at 60 cycles, provided only electrons occurring naturally in the gap are available to start the ionization.

At high frequency the voltage corresponding to a given sphere-gap depends on whether or not the spheres are acted upon by ultraviolet light, the effect of this light being to reduce the required voltage by about 3.5 per cent.

A fairly wide variation in the intensity of the ultraviolet light makes no perceptible difference in the voltage necessary to produce the flashover, although it probably does change the time necessary to set up the space charge.

That the space charge, when ultraviolet light is used, reaches a terminal condition in a small fraction of a second is shown by the theory. Our results corroborate this, as far as they go. For instance, while taking the run at 127,120 cycles, using ultraviolet light, a gap of 0.827 in. flashed across when the electroscope deflection was 61.1 deg. The reading was repeated, the gap being left at 0.827 in. and the voltage being brought up gradually until the deflection of the gold-leaf was 61.0 deg. This voltage was held for 3½ min. without a flashover taking place. The instant the deflection became 61.1 deg., the flash occurred, just as it had for the preceding reading. Evidently, when ultraviolet light is used, the distortion of the potential gradient occurs almost instantly, a wait of 3½ min. not changing it so much as one part in 600.

That this is not true when ionization is left to the ions found naturally in the air is demonstrated by the relative inaccuracy of the sphere-gap under these conditions.

Our tests disagree with the prediction of Peek that if the spheres are highly polished no difference should be found in the voltage required to spark across a given gap at high frequency and at 60 cycles. Moreover, we do not believe that a *slight* roughness has any appreciable effect. Undoubtedly, rough spheres will allow a spark to pass at a lower voltage than will polished spheres, the rough points forming starting points for corona, and for very rough spheres this effect will probably be greater at high frequency than at 60 cycles. The slight tarnish due to several hundred flashovers is not sufficient to show any such effect, however. At both 60 cycles and at high frequency our tests showed absolutely no difference in the spark-over voltage required, whether the spheres had just been polished on a power buffer or whether as many as 1000 flashovers had preceded the ones measured since the spheres were polished.

The effect of frequency on sparkover voltage between spheres depends on the distortion of the potential gradient by the positive space charge which accumulates in the gap at frequencies above about 20,000 cycles per sec. For each frequency the space charge which accumulates, and therefore the minimum voltage which will allow a spark to pass, depends on the relative ratio of production and of loss of positive ions.

The photoelectric action of ultraviolet light on the spheres makes available a large number of electrons in the gap at all times to start ionization. The difference in the rate of production of positive ions, thus brought about, explains the decreased voltage required when the spheres are flooded with ultraviolet light.

The increased percentage, as the frequency increases, of the positive ions which are held in the gap to form a space charge, explains the gradually decreasing voltage required to spark across a given gap as the frequency increases, up to 60,000 cycles per second.

The increased concentration of the space charge close to the surfaces of the spheres, with its consequent increased loss of ions by diffusion, explains the fact that above 60,000 cycles there is no further decrease in the voltage required to spark across a given gap, at least not until the frequency is above about 6,000,000 cycles for a one-cm. gap, when ionization by electrons alone should be sufficient to produce a spark, the electrons moving a distance less than the gap in a half-cycle, and therefore accumulating in the gap.

In conclusion we wish to express our debt to the many persons from whom we have received aid. Professors L. B. Loeb, C. L. Cory, and G. L. Greves have guided the research and helped with many valuable suggestions. Mr. R. P. Crippen worked jointly with the author in the early part of the investigation, and a large share of whatever of value the work contains should be credited to him.

We are indebted to the Regents of the University of California for financial assistance which made possible the research, and to the Federal Telegraph Co. for its generous loan for several months of a two-kw. Poulsen arc.

Mr. Pemberton and Mr. Cox of the University of California aided in the construction of the apparatus.

I would acknowledge with special gratitude the

splendid cooperation of my wife, who has worked with me far into the night for months in the accumulation of the experimental data, and whose cheery optimism throughout the research has been an inspiration.

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## Discussion

**H. J. Ryan:** The paper of Professor Reukema contains an important addition to the facts and their understanding regarding the frequency-voltage flashover relation of the sphere-gap voltmeter.

It may not be generally known that the voltages employed in some of the long-distance radio communication services are about on a par with those employed in long-distance transmission of power. The losses in the air and other insulating media functioning in the long-distance high-voltage radio transmitters occur at critical values, above which they increase with enormous rapidity.

It is vital, therefore, to have reliable means for measuring the crest values of such radio-frequency voltages. Because such voltages always conform closely to sine voltages, their effective values are deduced from reliable sphere-gap crest voltages with corresponding reliability.

The author has employed excellent strategy; he has most liberally applied well directed energy and enthusiasm to the study upon which the paper is based. I believe that his theory will be helpful in extending the calibrations and uses of the sphere-gap for all voltage frequencies and values.

Those taking up such work should remember the author's discovery of the effect of ultra-violet light upon the manner in which the sphere-gap voltmeter functions, and the promise it gives for the improvement of sphere-gap voltmeter consistency.

May I add just a word in regard to the point-gap discharge at radio-frequency high voltage. In 1915, one of my graduate students and I made a limited study of this subject, and from the results obtained at the time I can confirm the author's impression in regard to the behaviour of point-gaps. We employed a comparatively blunt point discharge to a plate. The plate was grounded; so was one terminal of the 88,000-cycle source. 46,000 volts discharged through 14 in. (See *Proc.* I. R. E., Vol. 3, p. 362.) The radio-frequency kv. per in. diminished as the distance from the blunt point to the plate was increased from 2 to 16 in. At 2 in. the kv. per in. equaled 4, and at 16 in., 1.4 kv. per in.

Regarding harmonics set up by the arc in these studies: The cathode-ray cyclograph was used to observe the presence or absence of harmonics in the undamped high-voltage radio-frequency waves developed by the arc. They were absent.

**R. J. C. Wood:** It is quite encouraging to find out what Professor Reukema has shown us,—that there is only 13 per cent diminution of voltage required over a given gap when the frequency increases up into the hundreds of thousands.

When we were going through the birth-pains of the 220-kv. lines, we were told in certain quarters that we were going to encounter a great deal of difficulty from high frequencies, which would enable comparatively small voltages to jump enormous distances. Very fortunately we seem to have established the fact that the higher frequencies do not exist in the line, so that removes that trouble, even if it were a fact that high frequency would jump great distances.

I should like to ask Professor Reukema whether he has carried this investigation beyond the point of using spheres—whether he has found any relation with point-gaps; presumably the decrease in the voltage between spark-points is considerably less at high frequencies than it is between spheres.

**F. O. McMillan:** I should like to ask Dr. Reukema whether he has done any experimental work on the measurement of high-frequency voltages with one sphere of the sphere-gap grounded. The published results as I understand the curves, are all for the ungrounded sphere-gap.

It may be possible that some of the reduction in the high-frequency sphere-gap spark-over voltages found in these experiments may have been due to the capacitance to ground of the apparatus shifting the voltage distribution on the dividing condensers for the electroscope during the high-frequency measurements, the voltage division becoming normal when the 60-cycle voltage was applied on account of the neutral ground on the 60-cycle transformer.

**D. I. Cone:** In the work of which this paper is a record extraordinary precautions were taken to test the presence of harmonics in the wave. I believe it would be helpful for Dr. Reukema to describe these tests more fully.

**Joseph Slepian:** Mr. Reukema has made a very valuable contribution to our knowledge of spark-over in air at atmospheric pressures, and in the development of an explanation of his results, has given us an extremely lucid picture of the Townsend theory of spark-over depending on the cumulative interaction of ionization produced by the collisions with molecules of both the positive and negative ions.

Lest there be misunderstanding, however, one point should be particularly stressed, and that is that the observed lowering of the sparking potential is a result of the application of *sustained* high-frequency voltage. If the voltage is applied in the form of rapidly damped pulses or wave trains, the sparking potential is raised and not lowered, as was shown by Leontiewa and Algermissen.

The success which Mr. Reukema has in explaining his results on the basis of the Townsend theory brings out sharply the dilemma to which Rogowski called attention recently in the *Archiv fur Elektrotechnik.* The Townsend theory has been extremely successful when applied to gases at low pressures, and even at atmospheric pressure will account for the observed relation between sparking potentials and electrode size and spacing. However, since it makes essential the ionization by collision of positive ions, it requires for the development of the spark a time at least longer than the time for a positive ion to traverse the spark-gap. Hence with Mr. Reukema's value of 39,600 cm. per sec. for the velocity of the positive ion under a gradient of 30,000 volts per cm. it would take at least 25 micro-seconds for the spark to develop for a 1-cm. gap. Actually, however, spark-over occurs in a fraction of a micro-second when potentials slightly above the sparking potential are applied. Until this difficulty is cleared up, the use of Townsend's theory at atmospheric pressures will be open to question.

It may be that simple ionization by collision is adequate to represent the very first stages of the development of the spark, but that after a certain critical density of ionization is reached, which takes only a very small fraction of a micro-second for ordinary sparking-potential experiments at atmospheric pressure, Townsend's description of the phenomena in terms of the two ionizing constants $\alpha$ and $\beta$ becomes inadequate. In that case Mr. Reukema's theory of the lowering of the sparking potential by sustained high frequency need concern itself only with the development of a critical density of ionization, and does not need to be tied up with the Townsend theory of the development of the spark itself.

**L. E. Reukema:** The first question concerns the effect of high frequency across needle-gaps as compared with the effect across the sphere-gap. It seems to me that the same factors would come in, but to a more pronounced degree when using needle-gaps. In sphere-gaps no corona can form before the break-down occurs. A positive space charge accumulates at high frequency, but no more corona would form than at 60 cycles, which is none at all. With needle-gaps we have corona forming, and the higher the frequency the greater the loss due to the formation of the corona. Whenever corona forms we have both electromagnetic radiation and increased temperature, both of which produce more ionization.

I have no experimental data on needle gaps, but I should say that the effect of high frequency on the needle-gap would be greater than on a sphere-gap.

As to the effect of grounding one sphere, naturally when one sphere is grounded a lower voltage will produce a flashover than if one is not grounded, simply due to the fact that this will distort the electrostatic field so as to produce a higher gradient at one sphere than would exist if one sphere were not grounded. However, it seems to me that grounding one sphere would not appreciably change the results we obtained at high frequency.

I did not make the test because the accuracy of my method depended on having the electroscope at essentially ground potential when I made the measurements. If one sphere were grounded, it would necessarily throw the electroscope off ground potential, which, as Mr. McMillan suggests, would introduce an error due to the capacity between the electroscope and ground.

Although I did not make the test, however, I thought of it quite thoroughly, and judging from the results obtained and the theory involved it seems to me that the results should be very nearly the same whether or not one sphere is grounded. The curves themselves would not hold, but the fact that the curves lie a certain percentage below the 60-cycle curve would hold. The same percentage drop should hold when one sphere is grounded as when it is not.

The possibility of error in the results due to the presence of harmonics in either 60-cycle or high-frequency waves has been suggested. Three years ago I had the privilege of talking this subject over with Dr. H. J. Ryan, and he told me then what he has told now, that the effect of the harmonics is negligible in the high-frequency wave obtained with the Poulsen arc, especially when the amount of inductance used is very large, as it was in my experiments.

However, to be absolutely sure that any harmonics present were negligible, careful tests were made with a wave meter. When testing for the fundamental frequency, the needle of the wave meter would be thrown off scale if the meter were brought closer than about 5 ft. from the inductance coils used. However, with the wave meter set for any harmonic of the fundamental, the meter could be brought right up to the coil, indeed, could be placed inside the coil, without any perceptible movement of the needle. Evidently, therefore, none of the harmonics was large enough to produce a perceptible deviation from a pure sine-wave form for the high-frequency waves.

For the production of the 60-cycle voltage an alternator was used which gave practically a pure sine wave. However, certain small irregularities in the wave form were brought in by the harmonics in the exciting current of the transformers used, these harmonics causing a very slight voltage drop in the transformers and a resultant slight change in wave form.

For that reason, on the high-tension side of the transformers, a series of oscillograms was taken for the range of voltage used in the tests. These oscillograms were then analyzed carefully. The maximum deviation of form factor of the waves tested from that of pure sine waves was 1.8 per cent, the average deviation was 0.8 per cent, certainly much too small to account for more than a negligible part of the 13 per cent decrease in flashover voltage found for high frequencies. Moreover, these deviations were definitely taken into account in plotting the curves, so that wave form could not bring in an error of more than about 0.1 per cent.

Mr. Slepian's statement that the results hold only for *sustained* high-frequency waves is important. For waves generated by Poulsen arcs, vacuum tubes, or high-frequency alternators the curves are accurate. For the damped waves of an impulse oscillator, they do not hold, since the time between successive wave trains is sufficient to change radically the space charge between the spheres, which is the cause of the decrease in flashover voltage at high frequency.

# The Space Charge That Surrounds a Conductor in Corona

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***Synopsis.****—A qualitative analysis of the nature of the space charge created about a conductor in corona, particularly with respect to relative magnitudes and polarities, rather than actual quantitative measurement, is described here. This work was the principal work on corona during the past year in the Ryan High-Voltage Laboratory.*

*In tests with the arrangements of a wire and a plane, and of a wire and a cylinder, a decided rectifying effect was discernible in the space about the conductor in corona, in that that region was built up to a unidirectional potential above ground, the magnitude and polarity of this potential depending on the voltage applied. In both of these set-ups, this net rectification, which is evidently caused by some differential action entering into the ionization process, was of a positive sign at the start of corona, but changed over to negative as the voltage was raised.*

*In a test made on two 1.1-in. diameter, parallel concentric strand copper conductors, 10 ft. apart, the space between them was found to have assumed a potential above ground when the conductors were in corona, the sign of this charge being negative at first, and then positive as the voltage increased. Tests were also carried out on a single brush, and on a rod fitted with "artificial" brushes.*

*In a corona-loss curve taken on the two cable conductors it was found that at the same voltage at which the sign of the rectified space charge had reversed, there was a "break" in the curve. This "break" corresponded to the point above which Peek's quadratic law of corona holds, and below which he has suggested the entrance of a probability relation.*

*A final field test was made at a span of the 220-kv. Pit River Lines of the Pacific Gas and Electric Co., in order to ascertain the magnitude and polarity of the charge built up about a high-voltage line in service. A negative polarity was found to be present as far down as 30 ft. below the conductors. Although the voltage was raised to 260 kv., the charge remained negative, indicating that the line at its normal 220-kv. potential was operating at a point on the corona-loss curve appreciably below that where the break occurs in the curve.*

## General Experimental Study of Space Charge

The continuation of the study of the nature of the space charge that surrounds a conductor in corona was made during the past year in the Ryan High-Voltage Laboratory by attacking the problem from several different angles.[7]

One of the simplest cases giving evidence of the presence of a space charge is in the time-honored set-up of the wire at the center of a cylinder. If the cylinder is connected to ground through a condenser and a d-c. galvanometer is shunted across the condenser and then alternating voltage is applied to the wire at the center of the cylinder, the galvanometer will indicate, in the usual set-up, the presence of a unidirectional current as soon as corona appears on the wire[3]. If the galvanometer shows a deflection, it indicates that some of the space charge that is planted about the conductor is getting over to the cylinder. Since the sign of the charge leaving the conductor reverses each time the voltage reverses, the deflection of the galvanometer indicates that charges of only one sign get over to the cylinder or that more of one sign than the other gets over. With the ordinary set-up, this unidirectional current is usually from the cylinder to ground at first but as the voltage is raised the galvanometer indicates a reversal of current. The reason for this will be taken up later.

If the wire and cylinder be replaced by a wire and neutral plane, the circuit connections being the same as those described in the use of the cylinder, the results obtained will be similar.

A little more as to the nature of the space charge can be learned by the set-up shown in Fig. 1. This method has been used by several others in the past and is not given here as anything new, but only to complete the story.[3,4] If, for example, the plate is made positive with respect to the wire mesh, part of the negative ions arriving at the wire mesh will be drawn through to the plate where they will give up their charge which will then produce a deflection of the galvanometer. The relative amount of the space charge arriving at the neutral plane can be observed under different conditions with respect to voltage, size of wire, distance of wire from plate, etc. A great deal of work has been done along this line by Mr. Willis.[4] A characteristic plot of results that were obtained by the authors using the method just described is given in Fig. 2. The curves show that the positive ions reach the neutral plane at a lower applied voltage on the wire than do the negative ions. The number of negative ions reaching the neutral plane, however, increases more rapidly with an increase in applied voltage than does the number of positive ions. If it were not for the fact that a single brush from a point has almost the same characteristic curves as those

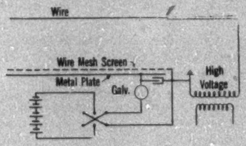

Fig. 1

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[7] See Bibliography for reference.

*Presented at the Pacific Coast Convention of A. I. E. E., Del Monte, Calif., Sept. 13-16, 1927.*

in Fig. 2, except with reverse polarity, it might not be so difficult to offer an explanation for the form of these two curves. If high-voltage direct current is applied to the wire instead of alternating current, and the corona current plotted against the applied voltage with the wire positive and then with the wire negative, the results will not differ much in form from those shown in Fig. 2.[5] Three of the factors that help to determine the form of these curves are the mobilities of the ions, their rate of manufacture and the amount that their presence disturbs the normal field.

One of the most important things is lacking in the results obtained by means of the set-up shown in Fig. 1 and that is the time element. In other words, what is the wave form of the current produced by the arrival of this space charge at the neutral plane? Since the action is cyclic, it was a comparatively easy matter to determine the form of this wave. The set-up shown in Fig. 3 was evolved. The principle made use of here is very simple: If a charged electroscope is brought near to a conductor in corona, it will be discharged, of course, by the attraction of the ions which will neutralize its charge. Now suppose instead of exposing the electroscope continuously, a synchronous shutter be provided that will expose it for only a certain portion of the cycle. If the rate of discharge of the electroscope be noted as the shutter is operated at different phase angles with respect to the applied voltage, the determination of the wave form can be made. This synchronous shutter arrangement was obtained by means of a four-pole synchronous motor driving a 12-in. aluminum disk with two radial slots 3.5 in. long and five deg. wide; see Fig. 3. This disk rotated under a metal plate in which there was a slot the same size as those in the disk and the position of the disk was such that the slot in the plate and a slot in the disk came in line once each cycle. When these slots coincided, the plate of the charged electroscope could draw through some of the ions that arrived at the metal plate, thereby discharging the electroscope. The rate of the discharge of the electroscope is a measure of the relative number of ions arriving at the neutral plane at that instant. The phase angle of the motor driving the disk was changed by means of a phase shifter and in this way the action over a complete cycle could be observed with the electroscope charged positively and then with it charged negatively. The electroscope was charged after each reading by means of a well-insulated switch, $S_1$. A 1050-kv-a., 60-cycle, sine wave generator was used in this work. To determine the phase position of the synchronous disk with respect to the applied voltage, a contactor $C$ was arranged on the disk so that it closed a circuit at the instant when the slot in the disk and the slot in the plate lined up. With switch No. 2 closed in the $A$ position, a click could be heard in the phones when the contactor closed the circuit. By shifting the phase angle of the revolving disk, a position on the phase shifter could be found where there was no click, which indicated the zero point of the voltage wave. Since the motor used could come into step with the disk in one of two phase positions, 180 deg. apart, it was necessary to be certain that this phase was the same each time the motor was started up. To do this, switch No. 2 was closed in $B$ position and with the phase shifter at the same angle each time the motor was made to come into step so that the d-c. voltmeter read positive.

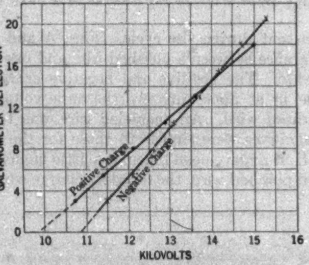

Fig. 2—Curves Showing the Amount of Positive and Negative Charge Arriving at the Neutral Plane in Relation to the Applied Voltage. A No. 14 Polished Copper Wire 5.5 in. from Neutral Plane.

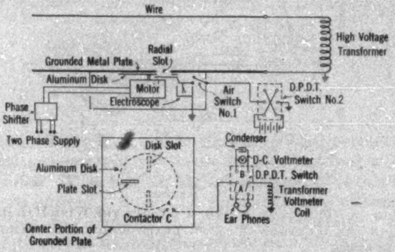

Fig. 3

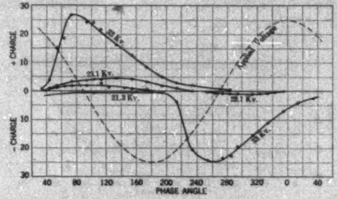

Fig. 4—Curves Showing the Relative Amount of Charge Arriving at the Neutral Plane at the Various Phases of the Voltage Cycle. A No. 14 Polished Copper Wire 5.5 in. from the Neutral Plane

The results obtained by this method are qualitative only but they give additional information that cannot be secured otherwise. Curves shown in Figs. 4, 5, and 6 were obtained by means of this set-up and will be discussed later.

Since the field about a wire above a neutral plane is not symmetrical, it was decided to find out what the effect on the form of the curves would be of a uniform radial field. The metal plate was replaced, therefore, by a 15-in. diameter metal cylinder having in it a slot which occupied the same position over the disk as the slot of the metal plate. The data for the curves shown in Figs. 7, 8, and 9 were then taken.

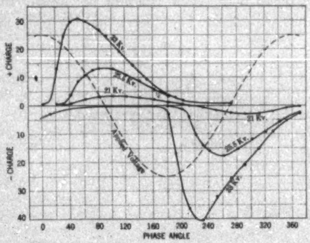

FIG. 5—THE SAME AS FIG. 4 EXCEPT THE WIRE HAD BEEN OUT IN THE WEATHER FOR TWO YEARS WHICH HAD OXIDIZED ITS SURFACE

The curves of Figs. 4 to 9 show that, except for magnitude, there is very little difference in the form of the positive and negative halves of the wave. A very important thing to note is the arrival of the charge at the neutral plane or cylinder sometime after the voltage on the wire has reversed.

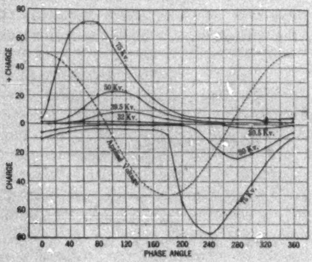

FIG. 6—THE SAME AS FIG. 4 EXCEPT A NO. 10 POLISHED ALUMINUM WIRE WAS USED; ITS DISTANCE FROM THE NEUTRAL PLANE WAS 10 IN.

There are two fields involved in the drive of the ions across the space, that of the wire itself and that due to the space charge, and the results have shown the latter field to be of considerable importance. In Figs. 4, 5, and 6, the positive charge continues to arrive at the grounded plate even after the voltage on the wire has reversed and reached its negative crest. This is also true for the negative charge and may be attributed to the diffused state of the ions caused by the unsymmetrical field between wire and plane. In the case of the cylinder where the field is radial, there is little or no time when there are ions of both signs present at the same instant during the cycle. Figs. 4 and 5 show the difference between a polished wire and one covered with oxide. The positive and negative charges seem to come in at approximately the same voltages with the oxidized wire. An enameled wire was tried also and the curves were similar to those for the oxidized wire. Had a curve been taken at a little higher voltage with the polished wire, the negative charge would have exceeded the positive as it did in the case shown in Fig. 6.

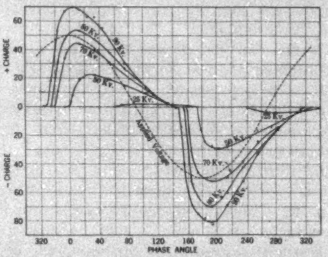

FIG. 7—THE SAME AS IN FIG. 4 EXCEPT FOR A NO. 16 POLISHED COPPER WIRE AT THE CENTER OF A 15-IN. CYLINDER

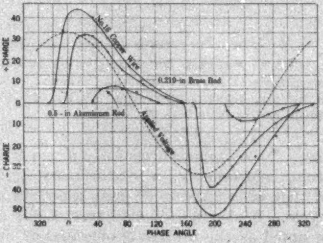

FIG. 8—CONDUCTORS OF DIFFERENT DIAMETERS AT THE CENTER OF A 15-IN. CYLINDER. APPLIED VOLTAGE HELD CONSTANT FOR ALL THREE AT 70 KV.

(Since the scale used for plotting the flow of charge was dependent upon the rate of fall of the leaf of the electroscope, which in turn was dependent upon the position and calibration of the electroscope, the only quantitative comparison of curves that can be made is: Fig. 4 with respect to Fig. 5 and Fig. 7 with respect to Fig. 8.)

It was found that curves obtained with a polished copper wire were practically identical with those secured with a polished aluminum wire of the same size under similar conditions.

In Fig. 9, with the kenotron in the wire circuit, the increase in the flow of charge is to be noted as the voltage on the wire goes over its crest having the same sign as the charge. This increase in the flow of charge is due only to the increase in the field driving the ions across.

Various attempts have been made to compute the movement of ions with conductors in corona. In order to do this, some have assumed varying mobilities for the ions which in our opinion is not justifiable until more data concerning the nature of this space charge are available.

If the distance from the wire to the grounded plane or cylinder be made sufficient, charges of both signs will not get across, but in no case in our tests was the distance so great that none of the charge of either sign got over when corona was present on the conductor. In fact, charges were found 30 ft. out from a conductor of a 220-kv. commercial power line on which there was but slight corona. This test will be discussed more fully later.

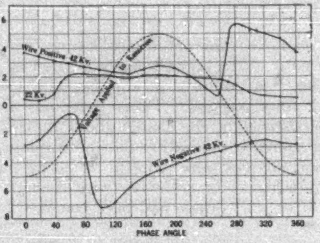

FIG. 9—SAME AS IN FIG. 7 EXCEPT VOLTAGE WAS APPLIED TO THE WIRE THROUGH A KENOTRON

For a limited space about a conductor in corona, the sign of the charge is reversed at each reversal of voltage. Beyond this space, charges of only one sign appear, which fact is undoubtedly due to a differential effect of the alternating charge near the conductor. The polarity of this charge is not the same for all conditions. In general, with an unpolished conductor out in the open, such as a transmission cable, the charge is negative at the first appearance of corona but as the voltage is raised it changes over to positive. If the wire is highly polished and near the neutral plane, however, the charge is positive at first and then negative. If the distance to the ground electrode is relatively great, the actual flow of rectified current to supply this outer charge is very small. In some cases, however, the potentials built up by the charges are fairly great.

If in the case of the wire and cylinder some method is used to neutralize or balance out the charging current from the cylinder to ground that would flow if corona were not present, the current that remains is commonly called the corona current. The latter is made up of two elements; namely, the ions that actually reach the cylinder and the bound charge that is drawn to the cylinder by the ions that leave the wire but do not get across. The question arose here as to what percentage of this current was due to the ions that arrived at the cylinder. The set-up in Fig. 10 was used to obtain the corona current. Below the corona starting voltage, a position was found on the potentiometer control such that there was no deflection of the cathode ray. This point, once found, would be the same for all voltages, so that when corona came in, the deflection of the cathode ray would be due to the voltage across the condenser, caused by the corona current only. The value of this voltage was determined from the amount of deflection of the cathode ray, and with the capacitance of the condenser known, the average value of the corona current was computed. The set-up in Fig. 11 was next used to determine the current produced by the ions actually reaching the cylinder. The principle is the same as that shown in Fig. 1. In this case, however, it was necessary to trap all the ions reaching the center section of the cylinder; therefore, a wire cylinder of ¼-in. mesh was fitted inside of the sheet metal cylinder with eighth-in. hard rubber strips separating the two. The main difficulty with this set-up was involved in completely separating the positive and negative ions.

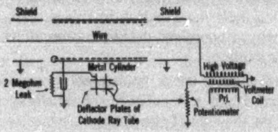

FIG. 10

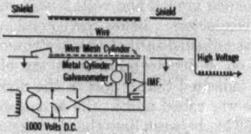

FIG. 11

With the a-c. voltage held constant on the wire, which was in corona, the d-c. voltage applied to the sheet metal cylinder was increased in steps from zero to 1000 volts and galvanometer readings were taken for each voltage. It was hoped that a plot of these values would give a saturation curve indicating a complete separation of the positive and negative ions, but this was not found possible in this case. A wire screen with smaller mesh was also tried but was even less effective. Using the average value of the current, however, as read by means of the galvanometer, when there was 1000-volt direct current on the metal cylinder, it was found in the case of the 0.219-in. brass rod with voltages above 50 kv., at least 70 per cent of the ions that left the wire reached the cylinder before they were drawn back to the wire by the reversal of voltage or were neutralized by the outgoing ions of the opposite sign. With a little modification in this set-up, there is no reason why a complete determination of this ratio could not be made.

Since the corona on a transmission conductor is made up largely, if not entirely, of brushes, a point was placed on the side of the 0.219-in. brass rod in the cylinder and the corona current studied with set-up of Fig. 11. At the first appearance of corona at 11 kv., the charge arriving at the cylinder was negative and remained negative until the positive began to get across at 40 kv. From 40 kv. to 48 kv., there was more positive than negative reaching the cylinder but from 48 kv. up to the flashover voltage the amount of the negative exceeded the positive. The point used was a piece of fine wire 1/16 in. long. The rod was then tried with two such points and it was found that the negative charge arriving at the cylinder always exceeded the positive, although it decreased slightly from 43 kv. to 45 kv.

## SPACE CHARGE SURROUNDING TRANSMISSION CONDUCTORS

The ionization about transmission conductors was next studied. Two concentric strand copper cables 1.1 in. in diameter and 50 ft. long were strung up in the laboratory parallel to each other and 10 ft. apart with a clearance of at least 20 ft. in all directions. A No. 16 wire was supported parallel to, and midway between, the two conductors. Hard rubber rods were used for insulators on this test wire and a lead from it was brought out at right angles to the plane of the two large conductors. An electroscope was connected between the test wire and ground and voltage was then applied to the two conductors. Below the corona voltage, the test wire was adjusted so that the electroscope showed no voltage on it due to position in the electrostatic field which indicated that it was in the neutral plane. The voltage was raised and at the first appearance of corona at 160 kv. between lines the electroscope showed a negative charge on the test wire. The negative potential increased on this wire as the applied voltage was raised until at 280 kv. between lines it was approximately 3000 volts. As the applied voltage was further raised, the potential on this test wire started to fall, slowly at first, then more rapidly, until at 300 kv. between lines it reached zero and then began to build up positive. At 500 kv. between lines the test wire had a positive potential of approximately 15,000 volts above ground. It was necessary to parallel the electroscope with a condenser to obtain the d-c. charge on the test wire when the applied voltage on the conductors was above 300 kv. Another test that was made with this set-up was to short-circuit the electroscope until the voltage had been taken off the large conductors and then the short circuit was removed. When this was done at 280 kv. the test wire accumulated sufficient negative charge to raise potential of the test wire several hundred volts. The same thing was tried at 400 kv. In this case, the potential on the test wire was over a thousand volts positive. These potentials were due to the persistence of the charge about the conductors after the source of ionization had been removed. In some cases, charges were found to build up potentials of a few hundred volts on the test wire as long as fifteen minutes after the voltage had been removed from the conductors.

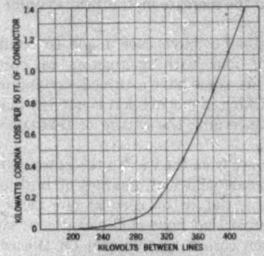

FIG. 12—CORONA LOSS CURVE FOR A 1.1-IN. CONCENTRIC STRAND COPPER CONDUCTOR. DISTANCE BETWEEN CONDUCTORS, 10 ft. INSULATOR LOSSES ARE NOT INCLUDED

A corona loss curve was then taken and is shown in Fig. 12. It is rather interesting to note that at 300 kv. between lines there is a break in the loss curve, and it is at this point that the potential of the charge about the conductors changes over from negative to positive. Above this point, Peek's quadratic law seems to hold, but below, it does not, and it is in this lower region that Peek has suggested a probability law.[6]

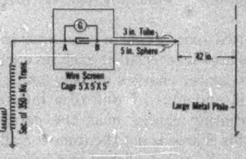

FIG. 13

Since the corona on these transmission cables appeared to be made up of individual brushes, it was decided to study the characteristics of a single brush. The set-up shown in Fig. 13 was used. An observer in the insulated screen cage at high voltage took all the necessary data. With this arrangement, the capacitance of the metal point is practically zero, so that the only current flow to and from the point is corona current. The simple connection of the condenser and galvanometer was the first one used. At the start of corona from the point which appeared as a soft glow, the galvanometer indicated a flow of negative current which increased until at 112 kv. the galvanometer deflection was two divisions. At this voltage, purplish streamers began to shoot out which considerably increased the luminosity of the brush. At 132 kv. the galvanometer had fallen to zero and at 140 kv. the current was positive, giving a deflection of two divisions. By this time the purple streamers had greatly increased and at 172 kv. the discharge was a large, well-developed brush giving a reading on the galvanometer of 10 divisions positive. The condenser and galvanometer were then replaced by the cathode ray tube. A 100,000-ohm resistance connected between the points *A* and *B* gave sufficient voltage drop to obtain a good deflection of the cathode ray that was proportional to the current. This current deflection was opened out into a current cyclogram by applying a sine wave voltage to the other pair of deflector plates. This sine wave voltage was obtained from a 2300-volt exciting winding connected to the high-voltage end of the secondary. This voltage had been tested and found to be a sine wave in phase with the secondary voltage. In order to put the important changes of current intensity in an advantageous position on the cyclogram for analysis, the phase angle of this timing voltage was shifted 90 deg. by means of a condenser. In the cyclograms shown in Figs. 14 and 15, the corona current appears to be a maximum shortly before the timing voltage impressed on the tube is zero, but due to the 90-deg. shift it can be seen that the maximum of the corona current is approximately 25 deg. ahead of the maximum of the voltage applied to the point. The form of these corona cyclograms would be altered slightly if they were changed over to a uniform time axis instead of the sinusoidal timing wave. The direction of rotation of the spot that traced these curves was carefully checked, as was also the polarity of the cathode ray tube deflectors. In Fig. 14, the positive and negative halves of the current wave are smooth and are practically the same. In Fig. 15 the negative side is still smooth but the positive side shows a sudden pulse of current. It was difficult to get the exact form of this pulse because the rapid movement of the spot did not leave a very distinct trace. Simultaneous with the appearance of this pulse of positive current, as the form changed from that shown in Fig. 14 to the one shown in Fig. 15, was the appearance of the long purple streamers. When a half-in. brass sphere was put over the end of the point, breaks appeared in the negative half of the current wave but they were not so prominent as those on the positive side. Time nor space does not permit much more to be said about these tests with the single brush. More work is to be done along these lines and a complete report will no doubt be made later.

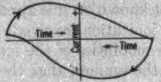

Fig. 14—Corona Current Cyclogram of a Brush from a Single Point. Voltage 100 Kv. 100,000-Ohm Shunt for Current Deflectors and 9400-Ohm Shunt for Timing Voltage

Current cyclograms were taken on the 1.1-in. transmission conductor previously mentioned with the charging current balanced out. While they were not so clear cut as those of the brush from the single point, they had the same general form. If all the brushes on the transmission conductor came in at the same voltage, the result, of course, would be practically the same as the brush from the single point except for magnitude. This is very nearly the case when voltage is not far above the corona starting voltage when there are only a few brushes present. Since this is within the economical range, the region we are most interested in, the authors believe that much can be learned about the mechanism of corona about the transmission line by the study of the brush from a single point. It is also their belief that results obtained from polished smooth surface conductors, especially if they are mounted near a neutral plane, are not applicable to transmission lines out in the open.

## Tests Made Under a 220-Kv. Transmission Line

In order to tie in the results obtained in the laboratory with those of actual operating conditions, the authors went to the 220-kv. lines of the Pacific Gas and Electric Co. at the Vaca-Dixon substation. The section under which the tests were made was that of a three-phase, 220-kv. line with 0.9-in. ropelay copper conductors in the horizontal configuration. The separation of the conductors was about 14 ft. and they were approximately 63 ft. above

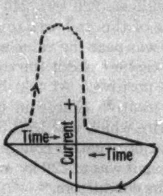

Fig. 15—Same as Fig. 14 Except 130 Kv. and 40,000 Ohms for Current Shunt and 4900 Ohms for Timing Voltage Shunt

the ground. At right angles to these conductors and 30 ft. under them, an exploring wire 33 ft. long was supported by hard rubber rods on long cotton cords. A lead was brought down from the exploring wire and connected to one side of a gold leaf electroscope the other side of which was connected to ground. In order to reduce the a-c. voltage due to position, the electroscope was paralleled by a 0.05 $\mu$ f. condenser the leakage of which was negligible. At first, a d-c. potential of 400 volts was applied to the wire which at the same time charged the condenser. The d-c. source was then removed and the rate of decrease of voltage on the condenser was observed by the fall of the leaf of the electroscope. With a positive charge on the wire, the voltage of the condenser dropped from 400 to 375 volts in three min. With the wire charged negative, there was no decrease in the condenser voltage for the same length of time. It was obvious then that there were only negative ions present in the vicinity of the exploring wire. This was the condition that was expected to be found in view of the results obtained in the previous laboratory tests. With no charge on the wire, the set-up was left untouched for an hour. At the end of this time the wire had picked up sufficient charge to raise the voltage on the condenser to 305 volts. The charge on the condenser was tested and found to be negative. It was observed that when a rather strong breeze was blowing, the ionization about the wire decreased considerably. This was to be expected with distances from the conductor as great as these.

The voltage was then taken off the section of line above the set-up and the exploring wire was raised until it was within 15 ft. of the conductors. The voltage was then supplied to this section of the line by means of a 40,000-kv-a. synchronous condenser driven by an induction motor. In this way the voltage applied to the line could be varied. Observations were made at three different voltages, 220 kv., 240 kv., and 260 kv. The main purpose of this test was to see if the normal operating voltage was near the value where the residual charge in the atmosphere about the conductor changed from negative to positive. At 260 kv. there was no evidence of any positive charge in the near vicinity of the exploring wire which was 15 ft. from the conductors. The amount of negative charge was found to be slightly greater than it was at 220 kv. with the exploring wire 30 ft. below the conductors.

### ACKNOWLEDGMENT

The authors greatly appreciate the generous cooperation of the Pacific Gas and Electric Co. and they are particularly indebted to H. F. Flynn and his assistants at the Vaca-Dixon substation for their invaluable aid in carrying out the test there.

### SUMMARY AND CONCLUSIONS

In the ionization process about a conductor or electrode in corona, there is a net rectifying action present whereby more charges of one sign assert themselves than of the other, so that the surrounding space is built up to a unidirectional potential above ground. Whether it is a case of the charges of the predominating sign being created more rapidly, or whether they endure longer than the others without being "wiped out" by recombination or return to the conducting circuit of the set-up, is not known, as it is apparently a part of the mechanism of ionization involved. It is probably determined by the mobilities of the ions, their rate of manufacture, and the amount that their presence disturbs the normal field.

For a given test arrangement, the magnitude and polarity of this rectified charge is dependent on the applied voltage. For the case of a polished wire and a grounded plane or cylinder, the sign of this charge is first positive, but soon drops to zero and then increases negatively as the voltage is raised. By placing a small "artificial" brush on the wire, it was possible to detect a slight negative rectification at the start of corona from it. The sign soon reversed, though, to positive as the voltage increased, and then to negative once more where it remained until flashover.

In a test with a single point projecting from a small sphere, the rectified space charge built up was first negative and then positive. The same was found to be true in the space between two 1.1-in. diameter cable conductors strung up in the laboratory. This would be expected since the corona on the surfaces of the stranded conductors would be, in reality, a mass of small single brushes, so that as a whole they would assume the characteristics of a single brush.

The fact that at the same voltage on the cable conductors at which the rectification of the charge reversed its polarity from negative to positive, there is a distinct "break" in the corresponding corona loss curve, proved of considerable interest. Since it is at this point that Peek's quadratic law relation begins to hold, it would seem from these tests that there is some governing factor contributed coincident with positive rectification to cause the ionization process to vary quadratically with respect to applied voltage. It is this upper portion of the curve that Dr. Ryan has referred to as that of "stable brush pattern." The lower portion he has called that of "unstable brush pattern," and it is here that Peek has suggested the entrance of a probability relation.

In the field test made on the 220-kv. Pit River Line of the Pacific Gas and Electric Company, which normally shows slight visible and audible signs of corona, it was apparent that the line was being operated at a point well below the "break" in the corona loss curve, as the space about the conductors was found to be charged negatively even when the voltage had been raised 20 per cent above the normal line voltage. Although the potential of the rectified charge is appreciable, the actual magnitude of the current necessary to supply it is negligible compared to the alternating space charge current itself.

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## Discussion

**L. F. Fuller:** It has been my privilege to discuss this work with the authors frequently during its progress and I have been impressed continually with the difficulty of the undertaking and the fact that it is pioneer work at the very forefront of our knowledge of things of this character.

Already it has had a very practical application of which I wish to tell you.

Several years ago it was observed that if a carrier-current telephone transmitter and receiver were connected at each end of a high-voltage transmission line in corona, a noisy, hissy sound was observed in the receiver whenever the carrier transmitter was started. The intensity of this noise increased with the power of the transmitter. This resulted in a noisy background to any speech transmitted over the line. No advantage could be gained by increasing the power of the transmitter because this increased the received signal and noise together, and the signal-noise ratio was not appreciably altered.

The reasons for this phenomenon appear to be closely related to the investigations of the authors. Within the radius of the space-charge cylinder surrounding each line conductor in corona, the ionization is much higher than in the space between conductors outside this radius. The atoms within the cylinder are in a decidedly turbulent condition and the conductivity is relatively high. Any radio-frequency current being passed between a coupling wire and line conductor must pass through this highly ionized region. The coupling wire and the line conductor associated with it do not form a condenser alone but rather a condenser in series with a microphonic rapidly changing resistor comprising the space-charge cylinder. The outer surface of this cylinder and the coupling wire may be considered as comprising the two plates of a condenser. Charging current through this condenser can reach the line conductor only by passing through this variable resistance. Thus the carrier is modulated by the variations of this series resistance and the typical hissing sound is heard in the receiver.

Some time ago Dr. Ryan in discussing space charge with me expressed the opinion that the substitution of coupling capacitors for coupling wires would thereby provide a metallic conductor in place of the variable resistor comprising the space-charge cylinder. This he thought might result in the elimination of the series modulation of the carrier and would remove the disagreeable hiss.

It is with a great deal of pleasure that I am able to report that this desirable result has been very thoroughly proved. Thus we have a practical example of the utility of space-charge studies of this character.

**R. J. C. Wood:** I didn't quite gather from the paper whether the voltage observed on the electroscope showed the natural gradient which would be in the air at that height whether the transmission line was there or not, or whether it showed as a resultant of the natural gradient and the voltage on the line, or whether it was due to the line alone.

In the first case the coupling rod was 30 ft. above the ground; in the second case it was 45 ft. above the ground; and with those heights above the ground one would expect a certain natural potential different to ground.

**C. H. Willis:** (communicated after adjournment) The evidence so far obtained regarding the diffused space charge which the authors found at some distance from the corona wires shows this charge to be quite erratic. However, I should like to ask if the authors think it possible that the sign of this diffused space charge at voltages slightly above the corona voltage, may not be determined by the sign of the corona which form at the lowest voltage, and therefore probably is produced in the greatest quantity at voltages a little above the corona voltage.

The curves shown in Figs. 4 to 9 inclusive give valuable information. The great lag of the space charge behind the electrostatic field shown particularly in Fig. 6 is surprising.

The break shown in the loss curve of Fig. 12 comes at about the voltage at which we should expect the two alternating space charges from opposite wires to meet as calculated from the mobility which has been found for ions in corona. When the two alternating space charges do meet the phenomenon changes to a case of gaseous conduction and it is to be expected that the loss curve will obey a different law. It would be quite interesting if this break could be shown to depend on the distance between the wires.

**J. S. Carroll:** Professor Reukema in his paper shows the short time required to clear the ions out of the space between the two spheres of a sphere-gap when 60-cycle voltage is used. In this case there is little chance of studying the movement of the ions. However, if the ions are supplied by one of the electrodes being in corona, such as a point or a small wire, the movement of the charge plays quite a different part. In that regard I should like to call attention to a few things brought out by the results shown in the curve of Fig. 9, in the paper by Lusignan and myself.

The voltage was applied to the wire at the center of a grounded cylinder by means of a kenotron connected to a high-voltage transformer. This voltage was of course unidirectional and pulsating. At a phase angle of 180 deg. the voltage applied to the wire is a maximum. No doubt the wire went into corona before this, but it is not until about a quarter of a cycle later that the charge sent out by this pulse of voltage gets over to the cylinder. The charge continues to arrive at the cylinder after this pulse gets across but gradually decreases in amount until at 270 deg. it is almost zero. Had the cycle been longer, that is the frequency a little lower, all the charge sent out at this voltage crest would have got across before the next pulse arrived.

It is interesting to note the slight increase in the amount of charge getting over at 180 deg. This is no doubt due to the increase in the resultant field caused by the rise in voltage applied to the wire. By resultant field I mean the field set up by the voltage applied between the wire and cylinder plus the field existing between the space charge and cylinder. This latter field is a very important factor in determining the movement of the ions in this and similar setups, so that it is very difficult to calculate ionic movements when a good part of the field that is producing this movement is attached to the moving ions themselves.

**J. T. Lusignan, Jr.:** Mr. Wood brings up the question as to how much of the unidirectional voltage which we measured beneath the outdoor transmission line was due to the natural gradient or the earth. Probably very little was involved as we got no detectable reading on the electroscope when the line voltage was off. Also we found the electroscope readings to increase as the potential of the line was raised. Our motive in making the test under a transmission line was prompted by the fact that we had found a unidirectional potential about conductors inside the laboratory where the earth's field would have no effect.

**J. S. Carroll:** Mr. Willis' question regarding the sign of this diffused space charge is not quite clear.

In order to determine the sign of the charge in the way suggested by Mr. Willis one would have to specify very carefully the conditions under which it would hold. For instance under certain cases the charges about polished conductors have opposite signs to those with rough conductors at the same impressed voltage.

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# Electric Oscillations in the Double-Circuit Three-Phase Transmission Line*

BY Y. SATOH[1]
Enrolled Student, A. I. E. E.

***Synopsis.**—This paper, after referring to the results of a previous study of the electric oscillations on the three-phase aerial line obtained by Dr. Bekku, describes the additional work done by the writer concerning the electric oscillations in the double-circuit, three-phase transmission line, and shows that there are three kinds of traveling waves. The nature of these waves, and some of the important results of the induced transients, are described. In the appendixes, it is shown briefly how these results were derived and how to calculate the line constants from the construction data of the lines. A few numerical examples are given.*

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IN 1923, Dr. S. Bekku deduced the theory of electric oscillations in the three-phase aerial line[2] and showed that, when the three phases are symmetrical, there arise two kinds of traveling waves having different surge impedances and, in general, different propagation velocities. He showed also that when the conductivity of earth is infinity, the propagation velocities of the two waves become equal to that of light.

Referring to his paper, the writer has discussed the oscillations in the double-circuit, three-phase transmission line which are of practical interest and has pointed out some of the important points obtained in studies of these oscillations.

### NATURE OF WAVES ON THE SINGLE- AND DOUBLE-CIRCUIT LINES

When a single conductor is running parallel to a boundary plane of a perfect conductor, the oscillation therein as is well known, consists of one kind of traveling wave having a propagation velocity equal to that of light. If, however, several conductors closely parallel one another, as in the case of ordinary transmission lines, there exist various kinds of traveling waves, due to mutual inductive effects. It was shown in Dr. Bekku's paper that in the three-phase line, if the three conductors are balanced, *i. e.*, if the transposition is complete, there are two varieties formed and there are two kinds of traveling waves. The first kind has currents and voltages the sums of which in the three conductors are zero, while the currents and voltages of the second are equal for three conductors. The first is a wave between conductors and the second is a wave between the group of conductors as one side and the ground as the other. The same theory applies to both aerial lines and underground cables.

If another three-phase circuit of the same electrical characteristics is closely coupled to the former circuit, as in the case of ordinary double-circuit, three-phase power lines, and if we assume that each conductor of one circuit is in the same position with respect to the conductors of the other circuit, then the oscillations therein are the superposition of three kinds of traveling waves, as follows: (The above assumption is not satisfied unless a special method of transposition is used, however, according to the numerical calculations for the actual lines, the assumed conditions are practically realized.)

1. The wave whose sums in voltages to ground and currents of the three conductors of each circuit are zero.
2. The wave whose voltages to ground and currents are equal for all of the six conductors.
3. The wave whose voltages to ground and currents are equal for the three conductors of one circuit and equal but opposite in sign for the three conductors of the other circuit.

Each of the above three kinds consists of two component waves traveling in opposite directions, and each current wave is accompanied by the corresponding voltage wave in the ratio of surge impedance; that is, each kind acts by itself as does the ordinary wave in the case of a single conductor.

The three kinds of waves may be stated as follows:

1. The first kind consists of two waves;
    a. The wave between conductors of the first circuit,
    b. The wave between conductors of the second circuit,
2. The second is the wave between the group of six conductors as one side and the ground as the other side.
3. The third is the wave between the group of three conductors of one circuit as one side and the group of three conductors of the other circuit as the other side. The three kinds are illustrated as in Fig. 1.

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*With supplementary discussion by H. G. Brinton.

[1] Graduate student, Stanford University.

[2] *Jl. of Japanese Inst. of E. E.*, Feb., 1923.

*Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., Sept. 13-16, 1927.*

Thus we see that a wave can never exist on one conductor only, but it is always accompanied by its companion waves on the other conductors. The surge impedances and the propagation velocities of these waves can be expressed as follows:

For the first kind,

$$Z_1 = \sqrt{(L - L_1)/(K - K_1)}, \quad (1)$$

$$v_1 = 1/\sqrt{(L - L_1)(K - K_1)}, \quad (1a)$$

For the second kind,

$$Z_2 = \sqrt{(L + 2L_1 + 3L_2)/(K + 2K_1 + 3K_2)}, \quad (2)$$

$$v_2 = 1/\sqrt{(L + 2L_1 + 3L_2)(K + 2K_1 + 3K_2)} \quad (2a)$$

For the third kind,

$$Z_3 = \sqrt{(L + 2L_1 - 3L_2)/(K + 2K_1 - 3K_2)}, \quad (3)$$

$$v_3 = 1/\sqrt{(L + 2L_1 - 3L_2)(K + 2K_1 - 3K_2)} \quad (3a)$$

in which

$L$ = Self inductance per unit length of a conductor with ground return,

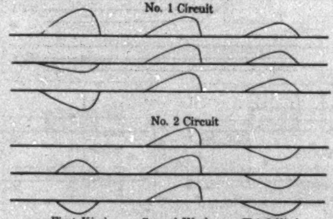

Fig. 1—Illustration of Three Kinds of Waves

$L_1$ = Mutual inductance per unit length between conductors of the same circuit with ground return.

$L_2$ = Mutual inductance per unit length between conductors of the different circuits,

$K$ = Coefficient of capacity per unit length of a conductor,

$K_1$ = Coefficient of static induction per unit length between conductors of the same circuit,

$K_2$ = Coefficient of static induction per unit length between conductors of the different circuits.

As is clear from the above expressions, the surge impedances and the propagation velocities of the three kinds of waves are different. If the conductivity of the earth is assumed to be infinity, the three velocities become equal to that of light.

The relative magnitudes of the three waves entering into the oscillation are determined by the initial conditions. For example, if equal charges are thrown on the conductors, as might be the case in a lightning stroke, only the second wave comes in. In three-phase switching operations there will exist only the first wave.

## REFLECTIONS AND REFRACTIONS

If the waves meet an irregularity, the reflections and refractions occur as in the case of a single conductor. If the irregularity is the same for the six conductors, each kind of wave independently obeys the same laws of reflection and refraction as in the single conductor. If, however, the irregularity is different in the various conductors, interference and splitting-up occurs among the different kinds of waves; *i. e.*, although the incoming wave is one kind, the reflected and refracted waves consist, in general, of three kinds. If the irregularity is the same for the conductors of the same circuit, the first wave acts separately from the other waves, being reflected without splitting-up, while there is splitting-up between the second and the third waves. For example, if the ends of the six conductors are grounded equally through the resistance $R$, then all waves obey the law, $G = -F(R - Z)/(R + Z)$, in which $F$ and $G$ are the incoming and reflecting current waves of one kind and $Z$ is the surge impedance corresponding to that kind. From the above formula, we see that when the six conductors are equally grounded with the resistance equal to the surge impedance of a certain kind of wave, the reflection is zero when the incoming wave is of that kind, but this is not the case for the incidence of the other waves.

When the line having the surge impedances $Z_1, Z_2, Z_3$, for the three kinds of waves is connected to another double-circuit, three-phase line of surge impedances $Z_1', Z_2', Z_3'$, then

$$G = F(Z - Z')/(Z + Z')$$

$$H = F \cdot 2Z/(Z + Z')$$

for each kind of waves, in which $H$ is the refracted current wave, that is, $H$ is the current wave that travels on past or through the irregularity.

When the conductors of the same phase of two circuits are tied together at the end of the line, as in the case of a paralleling bus, this end acts as an insulated end for the second wave and as a grounded end for the third wave, while for the first wave, there occurs no reflection; that is, the incoming wave on the first circuit passes through the tie bus and returns on the second circuit and vice versa.

## SOME OF THE EFFECTS OF INDUCED TRANSIENTS

From the above results we see that any oscillation in one conductor is always accompanied by corresponding oscillations in the other conductors. If, in the case of a single conductor, the conductor is grounded or broken on the way of the wave, the wave undergoes total reflection and cannot pass through the faulty point. In the case of three-phase lines, however, due to the inductive effects of the sound conductors, the waves do pass through such faulty points. Sound conductors must also stand the high voltage of waves due to induced transients from the nearby faulty conductor. The sound circuit must sometimes stand almost as much voltage as the faulty one. Waves starting on a single-circuit line will induce large transients in a sound circuit that may parallel the faulty circuit, even though the place of fault is some distance away from the point where the two circuits come together. This will be important because low-voltage lines often parallel high-voltage lines.

Since the sums of currents and voltages of the first and the third waves in six conductors are zero, they do not give inductive disturbances in adjacent lines. Inductive disturbances are caused only by the second kind of wave. The induced voltage resulting from the second kind of wave is obtained by multiplying by six the voltage induced by the individual conductor.

### EFFECT OF LOSSES

Due to the energy losses in the circuits, the waves gradually die out. In this case also each wave acts independently of the other waves and the whole theory obtained for the wave in the case of a single conductor can be applied to the individual wave. For example, each wave has its own attenuation constant and its wave front gradually flattens out just as if the other waves were absent.

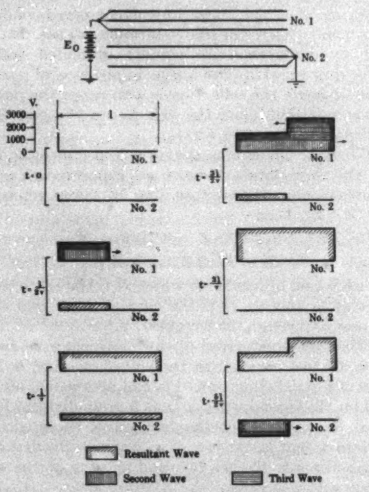

FIG. 2—VOLTAGE WAVES OF EX. 1

### EXAMPLES

Applying the theory outlined above to several cases one obtains the following results: In these examples, the following values of surge impedances were assumed: $Z_1 = 400$ ohms, for the first wave, $Z_2 = 1000$ ohms, for the second wave, $Z_3 = 500$ ohms, for the third wave. (These are typical values obtained for existing high-voltage lines.) When there is only one three-phase circuit having the same construction as one of the above double-circuit lines, $Z_1$ is the same as for the double-circuit case, while $Z_2$ is different and has the typical value $Z_2' = 800$ ohms.

1. *When the voltage source is suddenly connected to one of the circuits having the end conditions as shown in Fig. 2.*

The propagation and reflection of voltage waves when the source voltage is 1500 volts d-c. are shown in Fig. 2. The calculation of this example is shown in Appendix III.

In this figure, as well as in those that follow, the different kinds of waves are distinguished by different shadings so far as the clearness of the figures allows. As seen in Fig. 2, two kinds of waves are produced and the voltage wave of 1500 volts on No. 1 circuit is accompanied by the corresponding induced wave on No. 2. When these waves reach the right end, they are reflected. If this end of No. 2 circuit were insulated, or if No. 2 were absent, the maximum voltage in No. 1 would be twice the source voltage, but, affected by the grounding of the right end of the former, the maximum voltage in the latter is 1.8 times. The voltage of 0.85 times the source voltage is induced in No. 2 circuit.

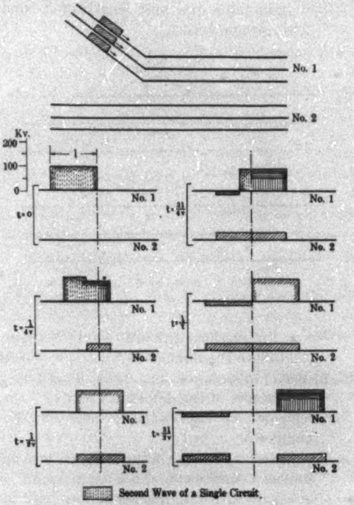

FIG. 3—VOLTAGE WAVES OF EX. 2

2. *When the wave comes from a single circuit.* (See Fig. 3.)

Fig. 3 shows how the voltage waves split up and give a disturbance in a parallel circuit when waves of 100 kv. between conductors and ground (second kind of wave), come equally on three conductors of a single circuit.

This case might arise from a lightning stroke on No. 1 circuit producing voltage waves that travel to a point where No. 1 parallels with No. 2. If the latter is the low-voltage circuit, the induced voltage may be sufficient to cause a flashover even though the trouble originated in No. 1.

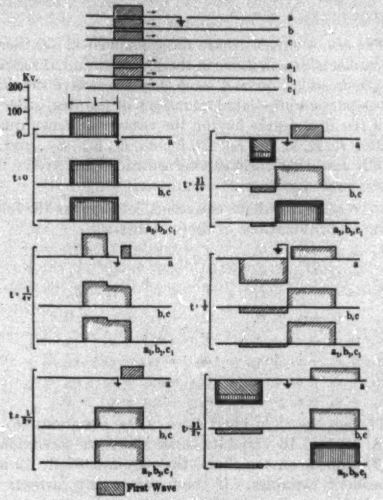

Fig. 4—Voltage Waves of Ex. 3

3. *When one of the conductors is broken and grounded on the way of waves.*

The state of reflections and refractions of voltage waves when the incoming wave is of the second kind of 100 kv., is shown in Fig. 4. As shown in Fig. 4, a considerable voltage wave passes the point at which the conductor is broken and grounded due to the inductive effect of the other conductors, and the fault in one of the conductors causes reflections on all of them.

4. *When the two circuits are tied together at one end, phases a and $a_1$ charged to 100 kv., and phases b and $b_1$, c and $c_1$ to −50 kv., then the other end of phase a is suddenly grounded, as the result of an insulator failure.* (The state of oscillation is shown in Fig. 5.)

An oscillation of this type could arise, if, in the double-circuit lines charged by a three-phase alternator through transformers, the distant end of a conductor is grounded at the instant when the voltage of this phase is maximum. The first few oscillations are represented approximately in Fig. 5 provided the length of the line is not large. This is because the impedances of the transformers are large for the high-frequency oscillation so that the phases may be considered approximately insulated from one another for a short time interval. As seen from Fig. 5, the voltage of 1.8 times the initial value is induced in phases $b$, $c$, $b_1$, and $c_1$ due to the sudden ground of phase $a$.

## Conclusions

1. The oscillation in the double-circuit, three-phase transmission line in general consists of three kinds of waves.

2. As the result of the existence of three kinds of waves, there are three kinds of surge impedances.

3. In a single conductor, reflecting waves can be made zero by grounding the end with a resistance equal to the surge impedance of the line. However, when there are three kinds of surge impedances, even if the six conductors are equally grounded with a certain resistance, the reflection may sometimes be zero, or sometimes otherwise.

4. When the waves meet an irregularity of the line, one kind of wave splits up into three kinds.

5. In a single conductor, if the conductor is grounded or broken on the way of traveling waves, total reflection occurs and the waves cannot propagate beyond that point. But, in three-phase lines, due to the inductive effects of the other wires, the waves do propagate beyond the point at which the conductor is grounded or broken.

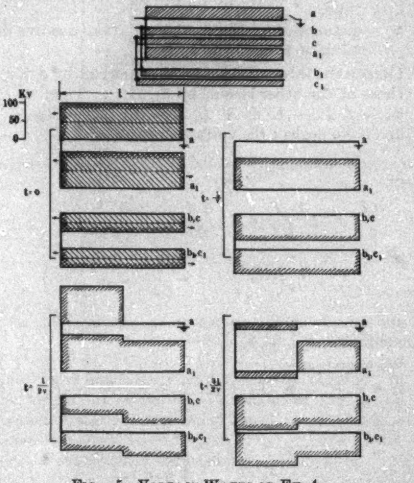

Fig. 5—Voltage Waves of Ex. 4

6. Due to the fault of one conductor, an appreciable voltage may be induced in the sound conductors; for instance, in example 4, due to the sudden ground of phase $a$, the voltage of 1.8 times the initial value is induced in the other phases.

7. Inductive interference to neighboring telephone circuits from the transmission lines is caused only by the second kind of wave and can be easily calculated.

The writer wishes to acknowledge the assistance rendered by Dr. F. E. Terman of Stanford University when this paper was prepared.

## Appendix I

### DERIVATION OF EQUATIONS AND THE METHOD OF SOLUTION

The following assumptions are made:

1. The characteristics of the two circuits are electrically the same.
2. The conductors in each circuit are in the same position with respect to one another and to the ground, *i. e.*, the transposition of each circuit is complete.
3. The conductors in one circuit are in the same position with respect to the conductors in the other circuit.

All the energy losses shall be neglected. Let $L$, $L_1$, $L_2$, $K$, $K_1$, and $K_2$ have the same meanings as in the main text. Let

$q$ = electric charge per unit length of a conductor,

$\phi$ = magnetic flux interlinkage per unit length of a conductor,

$E$ = voltage to ground of a conductor,

$I$ = current of a conductor,

$t$ = time,

$x$ = distance along the conductor, (take positive directions of $x$ and $I$ the same).

Denote the three conductors of one circuit by $a$, $b$, $c$, and those of the other circuit by $a_1$, $b_1$, $c_1$. Then we have,

$$\phi_a = L\, I_a + L_1\, I_b + L_1\, I_c + L_2\,(I_{a1} + I_{b1} + I_{c1}),$$

and if we neglect the voltage drop in earth,

$$-\partial E_a/\partial x = \partial \phi_a/\partial t,$$

or

$$\left.\begin{aligned} -\frac{\partial E_a}{\partial x} &= L\frac{\partial I_a}{\partial t} + L_1\frac{\partial I_b}{\partial t} + L_1\frac{\partial I_c}{\partial t} \\ &\quad + L_2\left(\frac{\partial I_{a1}}{\partial t} + \frac{\partial I_{b1}}{\partial t} + \frac{\partial I_{c1}}{\partial t}\right), \end{aligned}\right] \quad (4)$$

and exactly similar equations are obtained for conductors $b$, $c$, $a_1$, $b_1$, $c_1$.

We have further,

$$q_a = K\,E_a + K_1\,E_b + K_1\,E_c + K_2\,(E_{a1} + E_{b1} + E_{c1}), \quad (5a)$$

and

$$I_a = \frac{\partial}{\partial t}\int q_a\,d\,x,$$

or

$$-\frac{\partial I_a}{\partial x} = \frac{\partial q_a}{\partial t},$$

so that,

$$\left.\begin{aligned} -\frac{\partial I_a}{\partial x} &= K\frac{\partial E_a}{\partial t} + K_1\frac{\partial E_b}{\partial t} + K_1\frac{\partial E_c}{\partial t} \\ &\quad + K_2\left(\frac{\partial E_{a1}}{\partial t} + \frac{\partial E_{b1}}{\partial t} + \frac{\partial E_{c1}}{\partial t}\right), \end{aligned}\right] \quad (5)$$

and exactly similar equations are obtained for conductors, $b$, $c$, $a_1$, $b_1$, $c_1$.

The above equations are the fundamental equations of the electric oscillations in the double-circuit, three-phase transmission line, and since they are twelve simultaneous partial differential equations of the first order and of the first degree having the twelve unknown quantities, $I_a$, $I_b$, $I_c$, $I_{a1}$, $I_{b1}$, $I_{c1}$, $E_a$, $E_b$, $E_c$, $E_{a1}$, $E_{b1}$, and $E_{c1}$, it is seen that their general solutions are twelve indeterminate functions.

To solve the above equations, let us make the following transformations of the variables:

$$\left.\begin{aligned} I_a &= i_a + i_2 + i_3, & I_{a1} &= i_{a1} + i_2 - i_3, \\ I_b &= i_b + i_2 + i_3, & I_{b1} &= i_{b1} + i_2 - i_3, \\ I_c &= i_c + i_2 + i_3, & I_{c1} &= i_{c1} + i_2 - i_3, \end{aligned}\right] \quad (6)$$

$$i_a + i_b + i_c = 0, \qquad i_{a1} + i_{b1} + i_{c1} = 0. \quad (7)$$

$$\left.\begin{aligned} E_a &= e_a + e_2 + e_3, & E_{a1} &= e_{a1} + e_2 - e_3, \\ E_b &= e_b + e_2 + e_3, & E_{b1} &= e_{b1} + e_2 - e_3, \\ E_c &= e_c + e_2 + e_3, & E_{c1} &= e_{c1} + e_2 - e_3, \end{aligned}\right] \quad (8)$$

$$e_a + e_b + e_c = 0, \qquad e_{a1} + e_{b1} + e_{c1} = 0. \quad (9)$$

Though the right-hand sides of the equations (**6**) and (**8**) contain 16 variables, since there are 4 relations of (**7**) and (**9**) among them, they are essentially 12 independent variables. If these component currents and voltages are known, the currents and voltages of the six conductors are obtained by combining them according to equations (**6**) and (**8**). Hence, we shall now obtain these components.

Substitute (**6**) and (**8**) into the fundamental equations (**4**) and (**5**). By adding all the six equations of (**4**) and dividing by (**6**), we get,

$$-\partial e_2/\partial x = (L + 2\,L_1 + 3\,L_2)\,.\,\partial i_2/\partial t, \quad (10)$$

treating (**5**) the same as above,

$$-\partial i_2/\partial x = (K + 2\,K_1 + 3\,K_2)\,.\,\partial e_2/\partial t. \quad (10a)$$

By adding the three equations of $a$, $b$, $c$ of (**4**) and subtracting from it the three equations of $a_1$, $b_1$, $c_1$, and dividing by 6, we get

$$-\partial e_3/\partial x = (L + 2\,L_1 - 3\,L_2)\,.\,\partial i_3/\partial t, \quad (11)$$

treating (**5**) the same as above,

$$-\partial i_3/\partial x = (K + 2\,K_1 - 3\,K_2)\,.\,\partial e_3/\partial t. \quad (11a)$$

By subtracting (**10**) and (**11**) from the first equation of (**4**),

$$-\partial e_a/\partial x = (L - L_1)\,.\,\partial i_a/\partial t, \quad (12)$$

by subtracting (**10a**) and (**11a**) from the first equation of (**5**),

$$-\partial i_a/\partial x = (K - K_1)\,.\,\partial e_a/\partial t. \quad (12a)$$

Exactly the same equations as (**12**) and (**12a**) are obtained for $e_b$, $i_b$ . . . . $e_{c1}$, $i_{c1}$.

Equations (**10**), (**11**), (**12**,) (**10a**), (**11a**), and (**12a**) have the following forms:

$$-\partial e/\partial x = L \,.\, \partial i/\partial t, \qquad (13)$$

$$-\partial i/\partial x = K \,.\, \partial e/\partial t. \qquad (13a)$$

They are essentially the equations of oscillations in a single conductor having a self inductance per unit length $L$ and a capacitance per unit length $K$, the solutions of which are, as well known, two traveling waves propagating in the opposite directions and can be expressed as follows:

$$i = F(x - vt) + G(x + vt), \qquad (14)$$

$$e = Z \,.\, F(x - vt) - Z \,.\, G(x + vt), \qquad (14^1)$$

$$v = 1/\sqrt{LK} = \text{propagation velocity}, \qquad (15)$$

$$Z = \sqrt{L/K} = \text{surge impedance}. \qquad (16)$$

$F(x - vt)$ is a wave traveling in the positive direction of $x$, and $G(x + vt)$ in the negative direction of $x$. The forms of functions $F$ and $G$ can be determined from the boundary conditions.

If we apply the above results to equations (**10**), . . . (**12a**)$^1$, we get at once the solutions of component currents and voltages:

$$i_2 = F_2(x - v_2 t) + G_2(x + v_2 t), \qquad (17)$$

$$e_2 = Z_2[F_2(x - v_2 t) - G_2(x + v_2 t)], \qquad (17a)^1$$

$$i_3 = F_3(x - v_3 t) + G_3(x + v_3 t), \qquad (18)$$

$$e_3 = Z_3[F_3(x - v_3 t) - G_3(x + v_3 t)], \qquad (18a)^1$$

$$\left.\begin{aligned} i_a &= F_a(x - v_1 t) + G_a(x + v_1 t), \\ i_b &= F_b(x - v_1 t) + G_b(x + v_1 t), \\ &\ldots\ldots\ldots\ldots \end{aligned}\right] \qquad (19)$$

$$\left.\begin{aligned} e_a &= Z_1[F_a(x - v_1 t) - G_a(x + v_1 t)], \\ e_b &= Z_1[F_b(x - v_1 t) - G_b(x + v_1 t)], \\ &\ldots\ldots\ldots\ldots \end{aligned}\right] \qquad (19a)^1$$

in which $Z_1, v_1, Z_2, v_2, Z_3, v_3$ are as expressed by (**1**), (**1a**)$^1$, (**2**), (**2a**)$^1$, (**3**) and (**3a**)$^1$, and

$$\left.\begin{aligned} F_a + F_b + F_c &\equiv 0, \qquad G_a + G_b + G_c \equiv 0, \\ F_{a1} + F_{b1} + F_{c1} &\equiv 0, \qquad G_{a1} + G_{b1} + G_{c1} \equiv 0. \end{aligned}\right] \qquad (20)$$

By combining the above results according to equations (**6**) and (**8**), we get the general solutions of the oscillation: (omitting $(x - vt)$ and $x + vt$) ),

$$\left.\begin{aligned} I_a &= (F_a + G_a) + (F_2 + G_2) + (F_3 + G_3), \\ I_b &= (F_b + G_b) + (F_2 + G_2) + (F_3 + G_3), \\ I_c &= (F_c + G_c) + (F_2 + G_2) + (F_3 + G_3), \end{aligned}\right] \qquad (21)$$

$$\left.\begin{aligned} I_{a1} &= (F_{a1} + G_{a1}) + (F_2 + G_2) - (F_3 + G_3), \\ I_{b1} &= (F_{b1} + G_{b1}) + (F_2 + G_2) - (F_3 + G_3), \\ I_{c1} &= (F_{c1} + G_{c1}) + (F_2 + G_2) - (F_3 + G_3), \end{aligned}\right] \qquad (22)$$

$$\left.\begin{aligned} E_a &= Z_1(F_a - G_a) + Z_2(F_2 - G_2) + Z_3(F_3 - G_3), \\ E_b &= Z_1(F_b - G_b) + Z_2(F_2 - G_2) + Z_3(F_3 - G_3), \\ E_c &= Z_1(F_c - G_c) + Z_2(F_2 - G_2) + Z_3(F_3 - G_3), \end{aligned}\right] \qquad (21a)$$

$$\left.\begin{aligned} E_{a1} &= Z_1(F_{a1} - G_{a1}) + Z_2(F_2 - G_2) - Z_3(F_3 - G_3), \\ E_{b1} &= Z_1(F_{b1} - G_{b1}) + Z_2(F_2 - G_2) - Z_3(F_3 - G_3), \\ E_{c1} &= Z_1(F_{c1} - G_{c1}) + Z_2(F_2 - G_2) - Z_3(F_3 - G_3). \end{aligned}\right] \qquad (22a)$$

All $F$ waves travel in the positive direction of $x$ and all $G$ waves in the negative direction of $x$. By comparing the above equations with the description in the main text, it is seen that the first two terms of the above equations represent the first kind of wave, the second two terms the second kind of wave, and the third two terms the third kind of wave. The equations when the losses are considered can be treated in the same way and resolved into three sub-equations as above.

The forms of functions $F$'s and $G$'s are determined from the initial conditions. Let the distributions of currents and voltages on the six conductors at the instant at which the oscillation begins (when $t = 0$) be $J_a(x)$, $J_b(x)$, . . . . . $J_{c1}(x)$ and $V_a(x)$, $V_b(x)$, . . . $V_{c1}(x)$. Then we have,

$$J_a(x) = (F_a + G_a) + (F_2 + G_2) + (F_3 + G_3),$$

. . . . . . . .

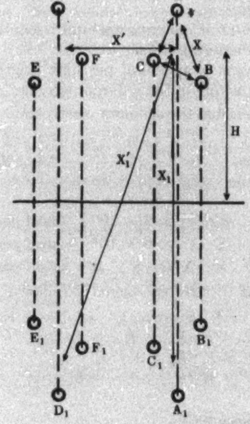

FIG. 6—DIMENSIONS OF LINES

$$V_a(x) = Z_1(F_a - G_a) + Z_2(F_2 - G_2) + Z_3(F_3 - G_3),$$

. . . . . . .

from which

$$F_a = (1/6)(2J_a - J_b - J_c) + (1/6\,Z_1)(2V_a - V_b - V_c),$$

$$G_a = (1/6)(2J_a - J_b - J_c) - (1/6\,Z_1)(2V_a - V_b - V_c),$$

and all other functions $F$ and $G$ can be obtained in similar forms. If we put $x - vt$ instead of $x$ in all the $F$ functions and $x + vt$ instead of $x$ in all the $G$ functions and combine them according to (**21**), . . . . (**22a**), we get the equations of oscillation.

## Appendix II

### CALCULATION OF LINE CONSTANTS

Assuming that the earth is a perfect conductor, the current in the earth is confined to its surface and the principle of electric image holds. Let the configuration of the lines be as in Fig. 6.

(In Fig. 6,

$$H = (1/2) \,.\, \sqrt[3]{A A_1 \,.\, B B_1 \,.\, C C_1} \,.$$

$$X = \sqrt[3]{A B \,.\, B C \,.\, C A} \,.$$

$$X_1 = \sqrt[3]{A B_1 \,.\, B C_1 \,.\, C A_1} \,.$$

$$X' = \sqrt[9]{(A F)^2 \,.\, (B F)^2 \, (B D)^2 \,.\, A D \,.\, B E \,.\, C F} \,.$$

$$X_1' = \sqrt[9]{(A F_1)^2 \,.\, (B F_1)^2 \,.\, (B D_1)^2 \,.\, A D_1 \,.\, B E_1 \,.\, C F_1} \,.$$

$r$ = radius of conductor.)

Then we get,

$$L = ((1/2) + 2 \,.\, \log \,.\, (2H/r)) \times 10^{-9} \quad \text{henry per cm.} \tag{23}$$

$$L_1 = 2 \,.\, \log \,.\, (X_1/X) \times 10^{-9} \quad \text{henry per cm.} \tag{24}$$

$$L_2 = 2 \,.\, \log \,.\, (X_1'/X') \times 10^{-9} \quad \text{henry per cm.} \tag{25}$$

Let

$P$ = coefficient of potential per unit length of a conductor,

$P_1$ = coefficient of potential per unit length between conductors of the same circuit,

$P_2$ = coefficient of potential per unit length between conductors of the different circuits,

then we have, from the ordinary electrostatics,

$$\left.\begin{aligned} E_a &= P \,.\, q_a + P_1 \,.\, q_b + P_1 \,.\, q_c + P_2(q_{a1} + q_{b1} + q_{c1}), \\ E_b &= P_1 \,.\, q_a + P \,.\, q_b + P_1 \,.\, q_c + P_2(q_{a1} + q_{b1} + q_{c1}), \\ &\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \end{aligned}\right] \tag{26}$$

where

$$P = 2 \,.\, \log \,.\, (2H/r) \times 9 \times 10^{11} \quad \text{daraf per cm.} \tag{27}$$

$$P_1 = 2 \,.\, \log \,.\, (X_1/X) \times 9 \times 10^{11} \quad \text{daraf per cm.} \tag{28}$$

$$P_2 = 2 \,.\, \log \,.\, (X_1'/X') \times 9 \times 10^{11} \quad \text{daraf per cm.} \tag{29}$$

Equations (**26**) can be rearranged as follows:

$$\left.\begin{aligned} q_a &= K \,.\, E_a + K_1 E_b + K_1 E_c \\ &\qquad + K_2(E_{a1} + E_{b1} + E_{c1}), \\ q_b &= K_1 \,.\, E_a + K \,.\, E_b + K_1 \,.\, E_c \\ &\qquad + K_2(E_{a1} + E_{b1} + E_{c1}), \\ &\qquad \cdots\cdots\cdots\cdots \end{aligned}\right] \tag{30}$$

see (**5a**) of Appendix I,
in which

$$K = \frac{(P + 2P_1)(P + P_1) - 6P_2^2}{(P - P_1)(P + 2P_1 + 3P_2)(P + 2P_1 - 3P_2)}, \tag{31}$$

$$K_1 = -\frac{(P + 2P_1)P_1 - 3P_2^2}{(P - P_1)(P + 2P_1 + 3P_2)(P + 2P_1 - 3P_2)}, \tag{32}$$

$$K_2 = -\frac{P_2}{(P + 2P_1 + 3P_2)(P + 2P_1 - 3P_2)}, \tag{33}$$

which are the required coefficients of capacity and induction. It is also seen that,

$$K - K_1 = 1/(P - P_1), \ \ldots . \tag{34}$$

$$K + 2K_1 + 3K_2 = 1/(P + 2P_1 + 3P_2), \ldots \tag{35}$$

$$K + 2K_1 - 3K_2 = 1/(P + 2P_1 - 3P_2). \ \ldots \tag{36}$$

From these results, the surge impedances and propagation velocities can be calculated. In this case, if we neglect the effect of magnetic flux inside the conductor, (if we drop 1/2 in the expression of $L$), we get $P/L = P_1/L_1 = P_2/L_2 = 9 \times 10^{20}$, so that $v_1 = v_2 = v_3 = 3 \times 10^{10}$ cm. per sec.

## Appendix III

### CALCULATION OF EX. 1.

From the symmetry of the line, we see that the first kind of wave is zero, and all $G$ waves are zero since, at first, only outgoing waves are present. Put $E_o$ = voltage of the source, $E_a = E_b = E_c = E$, $E_{a1} = E_{b1} = E_{c1} = E_1$, $I_a = I_b = I_c = I$, $I_{a1} = I_{b1} = I_{c1} = I_1$, then, $E = Z_2 F_2 + Z_3 F_3$, $E_1 = Z_2 F_2 - Z_3 F_3$, $I = F_2 + F_3$, $I_1 = F_2 - F_3$, (see (**21**), (**22**), (**21a**), (**22a**)) and at $x = 0$, $E = E_o$, $I_1 = 0$, whence, $F_2 = F_3 = E_o/(Z_2 + Z_3)$, and thus the outgoing waves are obtained.

When these waves reach the right end, the reflection occurs. Let $G_2$ and $G_3$ be reflected waves. Then

$$E = Z_2 (F_2 - G_2) + Z_3 (F_3 - G_3),$$

$$E_1 = Z_2 (F_2 - G_2) - Z_3 (F_3 - G_3),$$

$$I = (F_3 + G_2) + (F_3 + G_3),$$

$$I_1 = (F_2 + G_2) - (F_3 + G_3),$$

and at the right end

$$E_1 = 0, \ I = 0,$$

from which,

$$G_2 = F_2 (Z_2 - Z_3)/(Z_2 + Z_3) - F_3 \,.\, 2 Z_3/(Z_2 + Z_3),$$

$$G_3 = -F_2 \,.\, 2 Z_2/(Z_2 + Z_3) - F_3 \,.\, (Z_2 - Z_3)/(Z_2 + Z_3).$$

When the $G$ waves reach the left end, they are reflected. The left end of No. 1 acts as a grounded end, hence the reflection is the same as at the right end except No. 1 and No. 2 are interchanged. The oscillation at any instant can be found by superposing all these outgoing and reflected waves.

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## Discussion

**H. G. Brinton:** The paper by Mr. Satoh is rather mathematical and has been somewhat difficult to understand. It is based on a previous paper presented in Japan by Dr. Bekku, and perhaps Mr. Satoh assumes that the reader will look up the previous paper and so gives very little explanation himself. The writer has found it possible to understand the paper by first making an analysis from a physical standpoint and then checking Mr. Satoh's equations. As we have no other literature on this phase of the subject it appears desirable to give here a discussion of waves on several parallel wires.

The case to be discussed is that of two parallel three-phase lines. The three wave currents in the three wires of one line are $I_a$, $I_b$, and $I_c$. The three wave currents in the three wires of the other line are $I_a^1$, $I_b^1$, and $I_c^1$. The corresponding potentials of wires to earth are $E_a$, etc. Thus we have in general six traveling waves of different potential and current on six parallel wires. If we have only one wave on an isolated wire we would calculate the current and energy from the values of voltage and surge impedance, and we would calculate the changes in voltage due to reflection, etc. at points where the circuit constants changed. In the case of several waves on several adjacent wires, the problem is complicated by the magnetic and electrostatic interactions between the various waves. If we have six waves of different potential to consider, then there are six different surge impedances, or ratios of potential to current, to determine; and the surge impedance for each wave is affected by each of the different currents in the five other wires. Thus we have quite a complicated set of interactions and it is necessary to find a method evaluating them.

We shall first explain how it is possible to consider these six currents as the resultants of certain components and thus simplify the problem because of the simpler relations between these theoretical components. Consider first the three wave currents $I_a$, etc., in the three wires of one three-phase line. If we add these currents, taking account of direction, and then divide by three, we shall have the average value of current in these three wires. The actual current in each wire differs from the average. We shall call these differences $I_1$, $I_2$, and $I_3$. We know that the sum of these differences from the average value must be zero, because otherwise there would be an average difference from an average value which is impossible. Thus we see that the three unequal actual currents are composed of three equal components each having the average value and three unequal components whose sum is zero. In the same way we see that the three unequal currents in the other line are composed of similar components. We can now take the average of the three equal currents of one line plus the three equal currents of the other line. Let this value be called $I$. This value must be greater than the average value of one line by a certain amount, and less than the average value of the other line by the same amount which we shall call $I^1$. Then the value of the three equal components in one line is $I + I^1$ and the value of the three equal components in the other line is $I - I^1$. Thus we have reduced the six unequal wave currents in the six wires to the following components. In the three wires of each line there are three unequal components whose sum is zero. In the six wires there are six equal components called $I$ flowing in the same direction. In the three wires of one line there are three equal components called $I^1$ flowing in one direction; and in the three wires of the other line there are three equal components $-I^1$ flowing in the opposite direction to $I^1$ in the first line. A further simplification is obtained by considering the three unequal currents of each line whose sum is zero as equivalent to two equal and opposite currents. For example, if we wish to consider the surge impedance $Z_1$ of the wire in which $I_1$ is flowing, we can consider the two currents $I_2$ and $I_3$ as equivalent to a current $-I_1$ flowing in the opposite direction to $I_1$.

Then in considering the various components we have only equal currents to consider. When considering equal currents there is only one value of surge impedance to calculate. Thus we have reduced the problem to three sets of components and three surge impedances to be determined.

Before discussing these components further, it is well to state briefly the known relationships in the case of a single wire. In that case, if the wave potential at a given point is known, the wave current is found by dividing the potential by $Z_1$ the surge impedance. $Z$ is calculated from the formula

$$Z = \sqrt{\frac{L}{C}} \quad \text{but } v = \frac{1}{\sqrt{L\,C}} = \text{velocity of light}$$

$$\therefore Z = \frac{1}{c\,v} \qquad L = \frac{1}{C\,v^2}$$

$C$ is the capacitance to earth of a unit length of the wire and is twice the capacitance from the wire to its image.

If there is another wave of equal voltage and current on a second wire, then the capacitance of the first wire to earth is reduced or increased by the presence of the charge on the second wire, being reduced by a charge of the same sign and increased by a charge of the opposite sign. The capacitance will then be $C$ instead of $C$ per unit length. The inductance of the first wire is also affected by the current in the second wire, but if the waves travel with the velocity of light the product of capacitance and inductance remains constant and it is only necessary to calculate the capacitance as in the simple case of one wire. In the case of two wires the capacitance is then $\alpha\,C$ and the inductance is $\frac{1}{\alpha\,C\,v^2}$ and the surge impedance is

$$Z_1 = \frac{1}{\alpha\,C\,v}$$

This is the formula for surge impedance in the case of the component current $I_1$ and its opposite $-I_1$ in the first line, and also in the case of $I_1^1$ and $-I_1^1$ in the second line. If we assume, as Mr. Satoh does, that the two equal but opposite currents of one line would have zero resultant affect on the other line, then this formula for $Z_1$ holds true when these particular current components are flowing in the two lines at the same time. The voltage components corresponding to these current components are

$$\begin{aligned} E_1 &= I_1\,Z_1 & \qquad E_1^1 &= I_1^1\,Z_1 \\ E_2 &= I_2\,Z_1 & \qquad E_2^1 &= I_2^1\,Z_1 \\ E_3 &= I_3\,Z_1 & \qquad E_3^1 &= I_3^1\,Z_1^1 \end{aligned}$$

There is only one value of surge impedance for these components because the three wires of each line are assumed to be under the same influences. These assumptions do not correspond exactly to any conditions existing in practise, but they are satisfactory for the purpose of aiding us to obtain a fair general conception of the wave relationships.

We may next consider the current and voltage components in the case of the six equal components in the same direction in the six wires. In this case the capacitance of each wire to earth is reduced. If we assume, as Mr. Satoh does, that each wave is equally affected by the other five, then the capacitance of each wire is reduced by the same factor which we may designate as $B$. Then in the same way as above we see that the surge impedance of each wire is

$$Z_2 = \frac{1}{B\,C\,v}$$

We then have for each wire $E = Z_2\,I$

The third set of components to be considered are those consisting of three equal currents $I^1$ in one direction in the three wires of one circuit and three equal currents $-I^1$ in the opposite direction in the other circuit. In this case the capacitance to earth of one wire is $\gamma\,C$ instead of $C$. Assuming each of the six wires is under the same influences, this value $C$ applies to each wire. The corresponding value of surge impedance is

$$Z^1 = \frac{1}{\gamma\,C\,v}$$

In the above we have started with six waves of given current. In the same way we can start with six waves of given voltage and then calculate the wave currents after determining the surge impedances. For example, we would first find the average value $E$ for the six waves. The average value for one circuit would be $E + E^1$ and for the other circuit $E - E^1$. The differences $E_1$ and $E_1^1$ could then be determined, knowing the total voltages $E_a$ and $E_a^1$. After determining the various surge impedances $Z_1$ $Z$ and $Z^1$, the current components could be calculated and the total current in any wire would then be the sum of the components in that wire.

In order to determine the various surge impedances, it is necessary to calculate $C$ and the factors $\alpha, \beta$, and $\gamma$ which depend upon the amount that the capacitances are affected by the presence of the other charges. There are several ways of doing this. One way is to work with unit quantities and determine how much the potential at one wire is affected by the presence of the charges on the other wires. For example, in the case of $Z_1$ we have to consider two wires oppositely charged. The effect of the unit charge of one wire is to make it have the potential,

$$4.6 \log \frac{2\,h}{r}$$

where $h$ is the elevation of the wire and $r$ is its radius. The opposite charge on the second wire decreases the potential of the first wire by the amount,

$$4.6 \log \frac{r_2}{r_1}$$

where $r_1$ is the distance to the second wire and $r_2$ is the distance to its image. Therefore the potential of the first wire is decreased by the factor

$$\frac{\log \frac{2\,h}{r} - \log \frac{r_2}{r_1}}{\log \frac{2\,h}{r}}$$

Since in the case of unit given charge the voltage is inversely proportional to the capacity we can say that the capacity of the wire is increased by the factor

$$\alpha = \frac{\log \frac{2\,h}{r}}{\log \frac{2\,h}{r} - \log \frac{r_2}{r_1}}$$

The factor $B$ is determined in the same way, remembering that the charges are all of the same sign in this case and that there are six charges to be considered. Mr. Satoh uses an average value for the distance of the three wires of one circuit to one wire of the other circuit. Calling this distance $r_1{}^1$ and the distance to its image $r_2{}^1$ we see that the factor is

$$\beta = \frac{\log \frac{2\,h}{r}}{\log \frac{2\,h}{r} + 2 \log \frac{r_2}{r_1} + 3 \log \frac{r_2{}^1}{r_1{}^1}}$$

The factor $\gamma$ is calculated in the same way. Remembering that in this case the three charges of one circuit are opposite in sign to those of the other circuit, we see that

$$\gamma = \frac{\log \frac{2\,h}{r}}{\log \frac{2\,h}{r} + 2 \log \frac{r_2}{r_1} - 3 \log \frac{r_2{}^1}{r_1{}^1}}$$

Mr. Satoh does not use the above factors because he adds to or subtracts something from $C$ to take account of the effect of the other charges instead of multiplying $C$ by a factor. We have used the factor method for the sake of simplicity.

Mr. Satoh gives some interesting diagrams showing rectangular waves on parallel wires and the effect of certain changes in circuit constants. He gives the calculations for the case of three equal waves on three wires of one circuit due to an impressed d-c. voltage and three equal but smaller voltage waves on three wires of a parallel circuit due to induction from the first circuit. However, he apparently omits the calculation of the values of the induced wave which are the really important unknowns; and in the diagram the induced charges in the second circuit are incorrectly shown as having the same sign as the charges in the first circuit. These specific cases will require some further study and it therefore seems best to consider them separately. One point of interest to us is the fact that when waves of about equal voltage arrive at a station on the three wires of a circuit, which perhaps is the usual occurrence, the surge impedance is greater by a considerable percentage than in the case of a single wire, and so the wave current and energy is correspondingly less.

**R. J. C. Wood:** Some time ago we made some tests on 220-kv. lines of the Southern California Edison Company in order to get some idea of the frequency and magnitude of the surges that were actually occurring on the line. To help in this work the Westinghouse Company installed a number of klydonographs, and I wrote a paper about the results.

One of the main points brought out which had a bearing on the actual transmission line was that surges are quite rapidly damped in traveling along the lines.

Looking at the pictures of the waves shown in the paper one is led to think the wave is going to double up at the points of reflection, and amount to something which may be quite serious; but actually, on the line, these waves attenuate very fast. In fact we got measurements of surges about 100 or 150 per cent above normal at one station and 35 mi. away there was no indication on the instrument of there being any surge at all; this does not mean that there was no surge at all but that it had been reduced to not more than some 25 or 50 per cent above normal.

**E. R. Stauffacher:** There has been a number of cases on two 66-kv. lines single-tower, double-line construction, where the evidence of trouble on one of the lines has been found; but every indication regarding the relay operation pointed to the possibility of a trouble on the adjacent line.

I wonder if Mr. Terman would give us a little light as to what might have happened on the second line due to a wave of high voltage induced on the second line, when the trouble originated on the first line.

It would be one way of explaining some rather peculiar and erratic relay operations. Otherwise we have to accept the theory that the trouble was not cleared promptly enough on the first line in trouble and the arc went over into the other circuit.

**D. I. Cone:** This paper presents in clear perspective and in generalized form the propagation of waves in a double-circuit line. An illustration of the practical utilization of the three paths described occurs in the four-conductor arrangement common in communication practise comprising (1) two side circuits, one on each pair of wires; (2) "an earth return circuit using the four wires in parallel as one side," (The second path is very important from the standpoint of induction from external sources. It may also be used for communication purposes as in the simplex phantom telegraph circuit); and (3) a phantom "using each of these paths as one of its sides."

The impedances of the three paths for steady-state conditions at voice and higher frequencies are of the order of 700 ohms, 400 ohms, and 300 ohms respectively for circuits of the ordinary open-wire construction. These figures are closely similar to the surge-impedance figures for typical power circuits given in the paper.

The assumption is stated that the earth's surface is considered as a surface of infinite conductivity, giving a speed of propagation equal to that of light. In practise, for earth-return circuits the apparent speed of propagation, calculated from steady-state measurements may be less, by 20 per cent or more, due to such effects as the increased inductance per unit length of the circuit by reason of its penetration into the earth.

Mr. Satoh's seventh conclusion states: "Inductive interference to neighboring telephone circuits from the transmission lines is caused only by the second kind of wave and can be easily calculated," meaning the case of the several wires with earth return. He assumes throughout the situation in which the influence of each of the three conductors of any one of the circuits on its neighbors is the same; that is, that each circuit is so thoroughly transposed or the wires are so disposed with reference to this circuit that the influence of each of the three wires is the same on any outside circuit; and with that limitation the statement as made is correct. In the ordinary case that is not strictly true.

In the work of inductive coordination, the separations being secured in present practise are such, that often the only problem is that of the second kind of wave. These give an influence which spreads out to great separations.

**Joseph Slepian:** The work of Mr. Satoh is an interesting application of the resolution of a system of voltages and currents which are tied together by linear relations, into sets of normal components; that is into sets in each of which each voltage is proportional to its corresponding current.

The best example we have had before the Institute of the resolution of a system in this way was in the paper by Mr. C. L. Fortescue on Symmetrical Coordinates of nine years ago. In dealing with three-phase systems Mr. Fortescue resolved the line voltages and currents, $(E_a, E_b, E_c, I_a, I_b, I_c)$ into three sets of symmetrical components $(E_0, E_0\, E_0, I_0\, I_0, I_0)$, $(E_1, a^2 E_1, a E_1, I_1, a^2 I_1, a I_1)$, and $(E_2, a E_2, a^2 E_2, I_2, a I_2, a^2 I_2)$, where $a$ is a complex cube root of unity. Evidently in each of Mr. Fortescue's symmetrical components, each voltage is proportional to its corresponding current, and in addition to this simplicity to begin with, the equations for a symmetrical rotating machine take on the extremely simple form, $E_0 = Z_0 I_0$, $E_1 = Z_1 I_1$, $E_2 = Z_2 I_2$.

It is interesting to examine the general equations for the propagation of waves on parallel wires from this point of view and obtain the normal component waves of Bekku and Satoh. Neglecting resistances and leakages, and confining ourselves to the case of three wires, we have in general, if $E_a$, $E_b$, $E_c$ are the line voltages, and $I_a$, $I_b$, $I_c$ the corresponding line currents in a traveling wave, the three equations

$$\begin{aligned} E_a &= Z_{aa} I_a + Z_{ab} I_b + Z_{ac} I_c \\ E_b &= Z_{ba} I_a + Z_{bb} I_b + Z_{bc} I_c \\ E_c &= Z_{ca} I_a + Z_{cb} I_b + Z_{cc} I_c \end{aligned} \tag{1}$$

We then put the problem of finding a wave such that in it the corresponding voltages and currents are proportional, *i. e.*, such that $E_a = Z I_a$, $E_b = Z I_b$, $E_c = Z I_c$.

Substituting in the wave equations we get

$$\begin{aligned} 0 &= (Z_{aa} - Z)\, I_a + Z_{ab} I_b + Z_{ac} I_c \\ 0 &= Z_{ba} I_a + (Z_{bb} - Z)\, I_b + Z_{bc} I_c \\ 0 &= Z_{ca} I_a + Z_{cb} I_b + (Z_{cc} - Z)\, I_c \end{aligned} \tag{2}$$

In general this set of equations has only one solution namely $I_a = I_b = I_c = 0$. It will have other solutions, if and only if the determinant of the coefficients vanishes, that is, if

$$\begin{vmatrix} Z_{aa} - Z & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} - Z & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} - Z \end{vmatrix} = 0 \tag{3}$$

This is a cubic equation for $Z$, and in general, has three roots $Z_1$, $Z_2$, $Z_3$. There are then generally three normal component waves, each with its own surge impedance, $Z_1$, $Z_2$, or $Z_3$. The relation between the line currents or voltages in any one component wave is given by substituting the appropriate value of $Z$ in (2) and solving for the ratios between $I_a$, $I_b$, and $I_c$. Any arbitrary wave can be resolved into the sum of three normal component waves, and in terms of these normal components the wave equations (1) become

$$E_1 = Z_1 I_1 \qquad E_2 = Z_2 I_2 \text{ and } E_3 = Z_3 I_3 \tag{4}$$

When the three lines are completely transposed, as in the case considered by Bekku, we have $Z_{aa} = Z_{bb} = Z_{cc}$, and $Z_{ab} = Z_{ba} = Z_{bc} = Z_{cb} = Z_{ca} = Z_{ac} = 0$, and equation (3) reduces to

$$(Z_{aa} - Z_{ab} - Z)^2\, (Z_{aa} + 2\, Z_{ab} - Z) = 0 \tag{5}$$

This is a degenerate case in which two of the roots are equal, $Z_1 = Z_2 = Z_{aa} - Z_{ab}$, and the third root $Z_3 = Z_{aa} + 2\, Z_{ab}$. Two of the normal component waves become indistinguishable then. Applying equations (2) we find that for the first two normal component waves, (indistinguishable from each other) $I_a + I_b + I_c = 0$, and for the third wave, $I_a = I_b = I_c$. In any wave then in which $I_a + I_b + I_c = 0$, we will have $E_a = Z_1 I_a$, $E_b = Z_1 I_b$, $E_c = Z_1 I_c$, and in any wave in which $I_a = I_b = I_c$, we will have $E_a = Z_3 I_a$, $E_b = Z_3 I_b$, $E_c = Z_3 I_c$. Any arbitrary wave can be resolved into a superposition of two waves of these types.

The general case of six wires can be treated as above, leading to six normal component waves. Where the six wires consist of two sets of three, each completely transposed, the six component waves will degenerate into the three of Satoh.

**F. E. Terman:** I wish to begin by making some comments on the paper for myself. The value of Mr. Satoh's paper is that it gives a method whereby we can determine the magnitudes and effects of waves as they actually exist on the transmission line. The classical case of a wave between two conductors, given in our textbooks, fails in many instances to cover the practical situation.

By introducing slight modifications, Mr. Satoh's method of attack can be applied to cases other than the thoroughly transposed double-circuit three-phase line. For example, I think there would be no difficulty in solving the case of a three-phase line paralleled by a two-wire telephone line, and it seems that the same mode of attack might be of assistance in finding out something about the effect of a ground wire on waves. The ground wire is grounded at frequent intervals, which complicates the problem, but a solution for a simplified ideal case looks possible.

Since the author of this paper is now in Germany, I have the somewhat difficult task of taking the author's place in answering points that have been brought up.

In the supplementary discussion, Mr. Brinton gives a very good physical picture of the mathematical solution given in the paper. I do not agree with him on several points raised in the last paragraph of his discussion, however. The paper does include the induced transients. The equations for determining the magnitude of the induced transient are given in the example, and the induced waves are clearly shown in the figures, such as Circuit No. 2, Fig. 3. The signs of the waves as given by Mr. Satoh are also correct. These waves represent voltage, not charge, and it is even possible to raise a wire above ground potential without any net charge on it if the wire is in a suitable electrostatic field.

I remember Mr. Wood's article giving data on the attenuation of waves, and the unexpectedly high attenuation found for actual transmission lines undoubtedly does much to minimize the dangerous effects of lightning and other disturbances at some distances from the trouble. Near the origin of the trouble the effects are still severe for at such points the waves have not attenuated appreciably. The effect of the high attenuation is to localize the region of danger, but does not in any way influence the severity of the disturbance near the source of trouble, by doubling of voltage waves, etc.

Troubles such as described by Mr. Stauffacher might certainly be caused by induced waves, although a study of individual cases would be necessary to determine whether this was the real factor rather than other possible causes, when considering a specific type of trouble. The example given in Fig. 3 of the paper shows how trouble on one circuit will induce voltages on a second circuit, and if this induced wave reaches a transformer its voltage will double and might flash over a weak place.

Mr. Cone's remarks are interesting and to the point. It might be added that the reflection of the steady-state wave caused by the resistance of the transmission system is one of the reasons why the velocity of phase propagation in the steady state is not as great as the velocity of light.

The remarks of Dr. Slepian need no comment. They are complete in themselves, and I greatly enjoyed reading his clear statement of the general principles involved.

In conclusion I wish to state that this paper was written from material incorporated in a thesis Satoh wrote at Stanford, and the paper is very condensed compared with the thesis, which contains much more material than is presented here. For example, Satoh worked out 15 to 20 numerical examples, and the theory has been worked out better than space permits him to show in this paper. He has also worked out the solution of the double-circuit line under steady-state conditions, taking into account mutual inductive and electrostatic effects, and applied Fortescue's symmetrical-coordinate system to solve cases of unbalance. Another section of the thesis worked out the differential equations of the six-wire line not neglecting losses. His results give three waves, each attenuated by the losses independently of the presence or absence of other waves. The actual solution of these equations including losses was not made, but can be found in the literature of mathematical physics.

The thesis upon which this paper is based and which covers these additional parts, is in the Stanford Library, and is available to anyone who would find it useful.

# Transients Due to Short Circuits

## A Study of Tests Made on the Southern California Edison 220-Kv. System

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***Synopsis.***—*The paper deals with records which have been obtained during short circuits upon the Southern California Edison's 220-kv. system. The main features of the system are outlined, and such operating data as are necessary to afford an understanding of the various conditions which have to be met are included. The general scheme of relays is described, and the causes of flashovers and their times of occurrence are tabulated, together with the percentages which cause interruptions to service. Whether or not interruption is caused is found to depend, among other things, upon the load being carried at the time. With load below 150,000 kw., there are no interruptions unless relays are inoperative. A number of typical records of short circuits are shown and analyzed. It is shown that large amounts of power are consumed in short circuits, but that this is dependent upon the ground resistance. Practically all short circuits are single-phase to ground. The advantage of low-reactance machines is discussed and the various factors that prevent loss of synchronism pointed out. The records show that there is but little if any tendency for synchronous machines at either end of the line to fall out of step among themselves as a group, but that the sending end under certain conditions will get out of step with the receiving end.*

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### INTRODUCTION

THE ever increasing necessity of transmitting greater power over longer distances at higher voltages has led to considerable study during the last few years of the factors affecting the power limits of transmission systems. The ability of such a system to withstand short circuits without experiencing more than momentary disturbance is of the greatest importance in determining its economic capacity rating. The problem was first attacked by theoretical analysis, concentrating upon the steady state or static limits. Supplementary shop tests were made, in so far as a power system could be duplicated in miniature, but assurance was still lacking that the results obtained would apply to actual systems.

Subsequent analysis and observation of power systems indicated that their behavior during transients, such as those caused by short circuits and switching, was of the greatest importance. A very large amount of theoretical work was done in connection with this phase of the problem and an extensive series of tests was made upon the Pit River system of the Pacific Gas and Electric Co. The results of this work are described in two papers before the institute.[3] The close agreement between the results of the test and calculations indicated that any specific condition on a given system can be analyzed mathematically with a reasonable degree of accuracy, and the system designed accordingly. However, to obtain the over-all performance of a system, it is necessary to know not only its performance under stated conditions but also the character and frequency with which such conditions will be met in practise.

The Southern California Edison Company's Big Creek lines have been operated at 220 kv. since May 6, 1923. Prior to that time, no automatic relaying of sections of the line was in use. Since relays have been in operation, the larger percentage of faults have been cleared without interruption to service; some of the short circuits occurring at times of heavy load have caused the two ends of the system to go out of step even after proper elimination of a faulty section of line by relays. This has happened also as a result of heavy short circuits on 60-kv. lines out of 220-kv. substations.

In order to obtain information as to just what happened on this system under these abnormal conditions, special recording instruments were furnished by the Westinghouse Company and installed at a number of points upon the system. By their use, data as to the type of trouble and its effect upon the system have been recorded.

The purpose of this paper is to present the results of this investigation, which has been going on since August, 1925. Although the details of the disturbances encountered will undoubtedly be different on other systems in different localities, yet there will be points in common, and the range of conditions to be met will probably be of at least the same order on all systems, and the analysis be of more than local application.

### DESCRIPTION OF THE SYSTEM

The detailed description of the Big Creek System has been published many times and only the main items will be included in this paper.

The general design of the generating plants follows the unit system; that is, generator and transformer are connected as a unit to the higher-tension bus.

The single-line diagram of the Big Creek system,

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1. Southern California Edison Company, Los Angeles, Calif.
2. Westinghouse Electric & Mfg. Company, E. Pittsburgh, Pa.
3. *Studies of Transmission Stability*, by R. D. Evans and C. F. Wagner. *Practical Aspects of System Stability*, by Roy Wilkins, A. I. E. E. TRANS., Vol. 45, p. 41.

*Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., Sept. 13-16, 1927.*

Fig. 1, shows the unit system (220-kv.) at each station. A description of each machine at the 220-kv. stations is given in Table I.

The old Big Creek tower lines spaced 82 ft., center to center carry 605,000 cir. mil, aluminum conductors steel reinforced, spaced 17.25 ft., horizontally from Big Creek No. 1 to Eagle Rock. The Laguna Bell tap is of similar construction with 666,600-cir. mil, aluminum conductors steel reinforced, spaced 22.25 ft. with tower lines on 156-ft. centers. The new Vincent line with 1,033,500-cir. mil, aluminum conductors steel reinforced, spaced 22.25 ft. follows an entirely different right-of-way, averaging approximately 18 mi. east of the two lines.

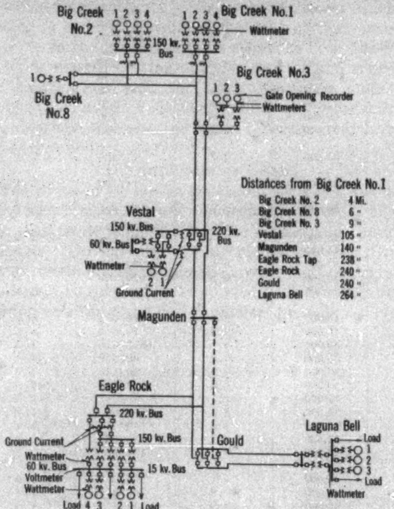
Big Creek No.2
1 2 3 4
150 kv. Bus
1 2 3 4
Big Creek No.1
Wattmeter
1
Big Creek No.8
Big Creek No.3
1 2 3
Gate Opening Recorder
Wattmeters
Distances from Big Creek No.1
Big Creek No. 2 4 Mi.
Big Creek No. 8 6 "
Big Creek No. 3 9 "
Vestal 105 "
Magunden 140 "
Eagle Rock Tap 238 "
Eagle Rock 240 "
Gould 240 "
Laguna Bell 264 "
Vestal
150 kv. Bus
60 kv. Bus
220 kv. Bus
Wattmeter
2 1
Ground Current
Magunden
Eagle Rock
220 kv. Bus
Ground Current
150 kv. Bus
Wattmeter
60 kv. Bus
15 kv. Bus
Voltmeter
Wattmeter
Load 4 3 2 1 Load
Gould
Laguna Bell
Load
1
2
3
Load
Wattmeter

Fig. 1

The Vestal substation was built primarily for the purpose of supplying power to the 60-cycle systems in the San Joaquin Valley, with an occasional interchange of power. It also serves as a switching and sectionalizing station for the 220-kv. lines.

Magunden and Gould are switching and sectionalizing stations only. Eagle Rock and Laguna Bell are the two main terminal stations from which the greater part of the power is distributed to the 60-kv. network.

At present, power from the Long Beach Steam Plant (total capacity of 200,000 kv-a.) is normally absorbed in the 60-kv. system; under certain conditions of load and during flashovers on the 220-kv. lines, steam power may be transmitted over 60-kv. lines through either or both Eagle Rock and Laguna Bell stations, the greater amount going through Laguna Bell on account of a more direct connection.

Kern River No. 3 (capacity 35,000 kv-a.) transmits power to Vestal over two 60-kv. lines. Other small plants are connected to the 60-kv. system at different points.

## 220-Kv. Relay System

Since the 220-kv. transmission system of the Southern California Edison Company is the backbone of the entire system, the importance of perfect automatic sectionalizing is supreme. Statistics show that approximately all failures on the 220-kv. lines are one phase to ground. Therefore the most important protection on these lines is the ground fault protection. Since faults must be cleared in a very short time to prevent interruption, a scheme that is not extremely fast in operation should not be used.

The study of protection against phase-to-phase faults is made by means of the ordinary calculating board; this alone is not sufficient, as protection is required against single-line faults to ground. The application of relays to satisfy this latter requirement requires the study of zero sequence, or residual currents.

For instance, due to the fact that the two Big Creek lines are relatively close together as compared to space separating them from the Vincent line and the return ground paths, the phase-to-ground reactance of the two Big Creek lines in parallel is only slightly less than the single Vincent line. Therefore, the Vincent line will have more ground fault current than either the Big Creek lines with ground faults north of Magunden or south of Gould. However, with one Big Creek line out, the other Big Creek line will balance up with the Vincent line.

Many relay schemes were devised and tried out on actual dummy systems. The one that proved most successful was the current balanced relays for phase-to-phase and phase-to-ground faults. All the Big Creek plants—Vestal, Magunden north, Eagle Rock, Gould south, and Laguna Bell - are equipped with two-line phase and ground balance current relays as shown schematically in Fig. 2. These are so connected that the tripping circuit is opened by auxiliary switches when either line oil switches are opened, thus leaving the second line in any one section non-automatic. Magunden, south, and Gould, north, are equipped with three-line phase and ground balanced relays. These are so connected that

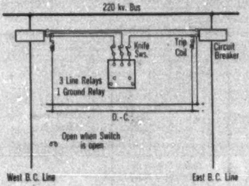
220 kv. Bus
Knife Sws.
Trip Coil
Circuit Breaker
3 Line Relays
1 Ground Relay
D.-C.
Open when Switch is open
West B.C. Line
East B.C. Line

Fig. 2

TABLE I
220-KV. STATION APPARATUS

| Synchronous machine | | | | Transformer | | | |
|---|---|---|---|---|---|---|---|
| Plant | Unit | Size in kv-a. | % leakage reactance | Size in kv-a. | % leakage reactance | Ratio | Connection |
| Big Creek No. 1.......... | Generator No. 1 | 17,500 | 22 | 17,500 | 8.2 | 6.6/150 | Δ/Y |
| | " No. 2 | 17,500 | 22 | 17,500 | 8.2 | 6.6/150 | Δ/Y |
| | " No. 3 | 17,500 | 22 | 17,500 | 8.2 | 6.6/150 | Δ/Y |
| | " No. 4 | 28,000 | 24.5 | 28,000 | 8.5 | 11/150 | Δ/Y |
| | | | | 52,500 | 9.6 | 150/220 | Y/Y |
| | | | | 52,500 | 9.6 | 150/220 | Y/Y |
| Big Creek No. 2.......... | Generator No. 1 | 17,500 | 24 | 17,500 | 8.5 | 6.6/150 | Δ/Y |
| | " No. 2 | 17,500 | 24 | 17,500 | 8.5 | 6.6/150 | Δ/Y |
| | " No. 3 | 17,500 | 24 | 17,500 | 8.5 | 6.6/150 | Δ/Y |
| | " No. 4 | 17,500 | 24 | 17,500 | 8.5 | 6.6/150 | Δ/Y |
| | | | | 52,500 | 9.6 | 150/220 | Y/Y |
| | | | | 52,500 | 9.6 | 150/220 | Y/Y |
| Big Creek No. 3.......... | Generator No. 1 | 28,000 | 20.8 } | 55,500 | 7.7 | 11/220 | Δ/Y |
| | " No. 2 | 28,000 | 20.8 } | | | | |
| | " No. 3 | 28,000 | 20.8 | 55,500 | 7.7 | 11/220 | Δ/Y |
| Big Creek No. 8.......... | Generator No. 1 | 25,000 | 12.7 | 60,000 | 12.3 | 11/220 | Δ/Y |
| Vestal.................. | Frequency changer { No. 1 | 15,000 | 22 | 13,500 | 8.7 | 150/15 | Δ/Δ |
| | Frequency changer { No. 2 | 15,000 | 23 | 15,000 | 9.3 | 69/12 | Y/Δ |
| | | | | 52,500 | 9.6 | 220/150 | Y/Y |
| | | | | 52,500 | 9.6 | 220/150 | Y/Y |
| | | | | 34,500 | 9 | 150/66 | Δ/Y |
| Eagle Rock.............. | Condenser No. 1 | 15,000 | 20.5 | 15,000 | 8.3 | 18/6.6 | Δ/Δ |
| | " No. 2 | 15,000 | 17.5 | 15,000 | 8.3 | 18/6.6 | Δ/Δ |
| | " No. 3 | 30,000 | 18.2 | 30,000 | 9 | 69.6/6.6 | Y/Δ |
| | " No. 4 | 30,000 | 22.5 | 35,000 | 10.8 | 69/6.6 | Y/Δ |
| | | | | 110,000 | 9.3 | 220/150 | Y/Y |
| | | | | 110,000 | 9.3 | 220/150 | Y/Y |
| | | | | 75,000 | 12.7 | 220/66 | Y/Δ |
| | | | | 34,500 | 8.7 | 150/66 | Δ/Y |
| | | | | 34,500 | 8.7 | 150/66 | Δ/Y |
| | | | | 13,500 | 8.2 | 135/15 | Δ/Δ |
| | | | | 13,500 | 8.7 | 135/15 | Δ/Δ |
| Laguna Bell............ | Condenser No. 1 | 30,000 | 13 | 30,000 | 9 | 69/6.6 | Y/Δ |
| | " No. 2 | 30,000 | 22.5 | 35,000 | 10.9 | 69/6.6 | Y/Δ |
| | " No. 3 | 30,000 | 22.5 | 35,000 | 10.9 | 69/6.6 | Y/Δ |
| | | | | 60,000 | 18 | 220/69 | Y/Δ |
| | | | | 60,000 | 18 | 220/69. | Y/Δ |

All transformers star-connected have neutrals solidly grounded.

if any one-line oil switches are opened the tripping circuits of the two sets of relays involved are opened, leaving balance protection between the remaining two lines in similar manner as above. Thus with two line switches opened the remaining line is non-automatic.

Since Eagle Rock is tapped off the two Big Creek lines near Gould, the perfect three-line balance between Magunden and Gould is destroyed. In order to keep the balance relays from functioning improperly an auxiliary relay is used that will open the tripping circuit of the two Big Creek lines from the relays that balance the two Big Creek lines with the Vincent line, allowing only the balanced relays between the two Big Creek lines for clearing trouble on either line. There is shown schematically the three-line balance current relays in Fig. 3. In case one Big Creek line is tripped out, this auxiliary relay, after a delay of from three to five seconds, closes the tripping circuit to the other Big Creek line, through the relay that is balanced with the Vincent line. With a fault just out of Gould on one Big Creek line, the first switch to open is that line switch at Gould. The instant after this switch has opened, the current in the other Big Creek line at Gould is much greater than the current in the Vincent line. But since the tripping circuit of Big Creek line side of this relay is interrupted, the good Big Creek line cannot be tripped. However, immediately the proper switches at Eagle Rock and Magunden open clearing the trouble. In a few seconds later the tripping circuit of the remaining Big Creek line is completed by the time delay auxiliary relay.

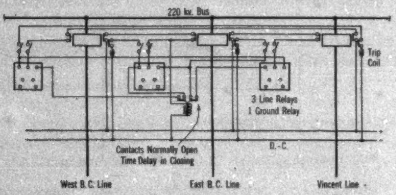

FIG. 3

## FLASHOVER SUPPRESSORS

In the case of trouble on the last or single line in any section, ordinarily the arc can be broken only by lowering the voltage of the system. This is done by actuating a time relay by means of ground current at all the Big Creek generating and 220-kv. substations, which, in some cases, trips the voltage regulator, and in others, starts a motor-driven rheostat to lower the exciter voltage of the generators and condensers. The motor-driven rheostats proved too slow and complicated and had a variable time of operation. This has been changed to a contactor which normally short-circuits an adjustable resistance in the exciter field and which is opened in cases of continued excessive ground current. As soon as the ground current ceases to flow, the contactor is closed, cutting out this resistor and allowing the exciters to pick up. The resistance must be properly adjusted; if too small, sufficient voltage drop is not obtained, whereas, too high a resistance may permit the exciter polarity to reverse.

## DISTRIBUTION OF LOADS

The division of power generated at Big Creek and Long Beach steam plants varies greatly throughout the year and is dependent upon the season and the load demand. During the spring run-off at Big Creek plants, these plants supply the greater part of the load, the steam being used for supplying peak demands only. During this time and early summer the main reservoir, (Huntington Lake reservoir with a capacity of 88,000 acre-ft.) is filled.

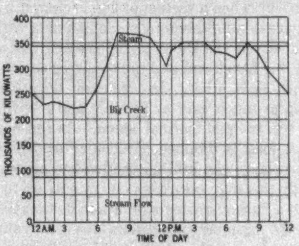

FIG. 4

The heaviest loads occur during the months of June, July, and August. Thus, after the run-off period and the lake has been filled, steam and stream flow plants run on block loads, and Big Creek plants use stored water for making up peak loads. The stored water has to supply peak power up to the time of next run-off; therefore, the rate at which the stored water is used is somewhat fixed, accounting for a definite amount of power; the remainder of the demand is supplied by steam.

The period of spring run-off is illustrated by Fig. 4—the daily load chart for June 8, 1926. The maximum hydraulic output possible was the maximum rating of the machines at this time, or 345,000 kw. None of the stream-flow plants has storage; their output is equivalent to the actual stream flow at any time. Since the load exceeded the total hydro generation, it was necessary to supply the peak loads with steam as indicated. It will be noticed that the maximum demand at Big Creek was 257,000 kw. and the minimum was 132,000 kw., the low load being from 12:00 midnight to 6:00 a. m.

The period after the run-off is shown by Fig. 5, the daily load chart of July 27, 1926. The steam plant supplied a constant load of 110,000 kw., while the remaining portion of the load ranging from 50,000 kw. to 210,000 kw. was supplied by the Big Creek plants, the low load again being between 12:00 midnight and 6:00 a. m.

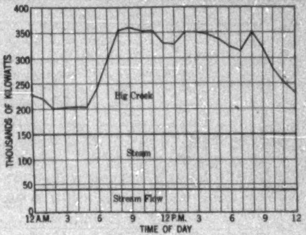

FIG. 5

Fig. 6 is a yearly kw-hr. output chart showing the distribution of energy between the Big Creek plants and the Long Beach Steam Plant. It can be seen that during the months of April, May, and June a very small amount of steam power is generated. The transformer capacity at the various substations on the Big Creek lines is shown by Table I.

## POWER DISPATCHING AND GOVERNING

The production engineer, having charts and measurements of the behavior of the whole system calculates from this information the amount of load to be carried at the various plants. Accordingly, the men in charge of the plants are informed as to the amount of power to be generated. The general method of operation is to have one plant do the regulating while the others carry block loads.

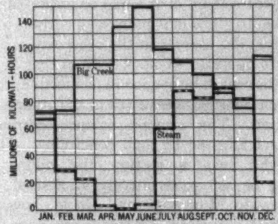

FIG. 6

## OPERATION OF RELAYS

The normal operation on the 220-kv. lines is to have the balanced relays in service. When a fault occurs near one station it generally clears at that station first due to the greater unbalance. Since the relay trip circuits are interlocked to be automatic only when both line switches are closed, the relays, after one line has opened, automatically become non-automatic. In order to have protection upon the faulty line when testing, it is necessary to arrange the balanced current relay to trip on that line only. Therefore, knife switches are properly connected for the purpose. In case the line trouble has been removed, the switch will remain closed, and in order to re-establish load over this line, the balance current relays are then made non-automatic at each end of the section, the oil switch being closed in at the other end of the line. The relays are then made automatic.

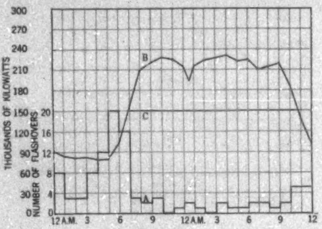

FIG. 7

When all the 220-kv. lines are automatic the flashover suppressors are left out of service. But when a section of one line is out for repair, or otherwise, and the remaining line in this section is non-automatic, the flashover suppressors are placed in service. In case a flashover occurs on this one section of line, the flashover suppressors will operate. If, however, the fault should occur on a section of lines where relay protection is in service the relays will clear the fault before the flashover suppressors are brought into action, due to the fact that the suppressors have a minimum definite time of operation sufficient to allow clearance of line by line relays.

The current setting of the line balance relays is sufficiently high to allow maximum load current to flow on one line with zero current in the other without causing the relays to operate. This is done so that if, by accident, one line switch be opened in one section, the relays will not open the good line switch at the other end of the same section. The ground balance current relay setting is not affected by load conditions. Therefore, in a straight, two-line section, the ground balance relays may be set as sensitively as desired. In the section between Magunden and Gould, however, the ground relays balancing the Big Creek lines with the Vincent line must be set so high that the unbalanced ground current due to the difference of ground impedance of the three lines, with a through, short-circuit, is insufficient to operate the relays.

## TIME AND CAUSES OF FLASHOVERS

The total number of flashovers on the 220-kv. lines from January 1, 1924 to May 1, 1927, occurring during the various hours of the day is shown by Curve *A*, Fig. 7. Curve *B* is an average daily load curve for one year. It will be seen that most of the flashovers have occurred between the hours of 3 a. m. to 7 a. m., during the light load period. Line *C*, indicating the load below which flashover does not cause outage shows correct relay operation and will be discussed later. (Refer also to Fig. 8.)

TABLE II
CAUSES OF FLASHOVERS

| | | |
|---|---|---|
| Bird trouble.................... | 82* | phase to ground |
| Bushing flashover............... | 3 | " |
| Fire under line................. | 2 | " |
| Hay derrick in line............. | 2 | " |
| Wire of Ford spark coil thrown in line.................... | 1 | " |
| Vine in line.................... | 1 | " |
| Bus flashover................... | 1 | " |
| Cable splice broke.............. | 1 | " |
| Disconnect fell open............ | 1 | " |
| Unknown......................... | 2 | " |

*One of these flashovers, due to strong wind, blew from phase to ground to phase to phase to ground.

Table II shows the causes of flashovers, also the kind of flashover; phase-to-phase, or phase-to-ground.

Table III shows the data of flashovers on 220-kv. lines occurring during the period of tests.

## RESTORATION OF SERVICE

Ordinarily when a section of line is cleared by relays, the service is not interrupted. Some times, with heavy loads, however, the shock to the system is too great and the Big Creek end and the receiving end fall out of step with each other. In this case, the steam plant picks up as much load as possible and the Big Creek plants try to hold normal speed. In the meantime, sufficient load is dropped, accidently or otherwise, so that the plants can pull up the load to normal speed. Normally this may take from one minute up to several.

When a flashover occurs on a non-automatic section of line, the flashover suppressors lower the voltage and as soon as the arc breaks bring the voltage up. The devices are timed to make this complete operation in 15 sec. Sometimes, at heavily loaded periods, the driving force at Big Creek pulls out of step with the rest of the system by over speeding. The system is brought back together in a similar way as above but usually takes a little longer.

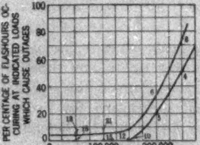

FIG. 8

## SYSTEM OUTAGE

The proportion of times the system is likely to be put out of service due to flashovers is variable, depending upon the load, system connections, and the severity of the trouble.

Fig. 8 is a chart showing what the percentage of

TABLE III

| Date | Connected kv-a. | Big Creek generation | Total ground amperes | Location of fault | Relay operation | System operation |
|---|---|---|---|---|---|---|
| | | | 1925 | | | |
| 8-23 | 245,000 | 31,000 | 1080 | 127 | ⊙ | |
| 8-26 | 265,500 | 64,000 | 1050 | Eagle Bell | ▲ | |
| 8-27 | 280,500 | 53,000 | 850 | Laguna Bell | ⊙ | |
| 9-3 | 424,500 | 201,000 | 1140 | Bus B. C. No. 1 | ▲ | * |
| 9-8 | 340,500 | 131,000 | 980 | 141 | ▲ | |
| 9-13 | 248,000 | 21,000 | 1080 | 102 | ⊙ | |
| 9-21 | 197,500 | 25,000 | 580 | 59 | ⊙ | |
| 10-2 | 381,000 | 146,000 | 610 | 136 | ⊙ | |
| 10-3 | 248,000 | 60,000 | 1060 | 142 | ⊠ | * |
| 10-18 | 239,000 | 72,000 | 1110 | 126 | ⊙ | |
| 10-19 | 160,000 | 0 | 770 | 95 | ⊙ | |
| 10-21 | 207,500 | 26,000 | 800 | 103 | ⊙ | |
| 10-25 | 361,500 | 97,000 | 230 | .. | ⊙ | |
| 10-25 | 359,500 | 144,000 | 1030 | 77 | ⊙ | |
| 10-26 | 245,500 | 72,000 | 1150 | 95 | ⊙ | |
| 10-30 | 275,500 | 69,000 | 1190 | 84 | ⊙ | |
| 11-4 | 290,500 | 48,000 | 1280 | 115 | ⊙ | |
| 11-6 | 235,500 | 59,000 | 685 | 60 | ⊙ | |
| 11-7 | 260,500 | 71,000 | 1190 | 112 | ⊙ | |
| 11-16 | 439,500 | 206,000 | 1945 | 212 | ▲ | * |
| 11-23 | 207,500 | 22,000 | 1030 | 99 | ⊙ | |
| 11-27 | 235,500 | 46,000 | 1040 | 167 | ⊗ | |
| 12-13 | 243,000 | 47,000 | 690 | 138 | ⊙ | |
| 12-18 | 308,000 | 100,000 | 1230 | 96 | ⊙ | |
| 12-23 | 351,000 | 100,000 | 850 | 8 | ⊙ | |
| | | | 1926 | | | |
| 1-2 | 200,500 | 13,000 | 560 | 60 | ⊙ | |
| 1-15 | 207,500 | 17,000 | 1050 | 123 | ⊙ | |
| 1-16 | 237,500 | 52,000 | 1080 | 95 | ⊙ | |
| 1-18 | 207,500 | 5,000 | 930 | 88 | ⊙ | |
| 1-25 | 218,000 | 5,000 | 1050 | 64 | ⊙ | |
| 2-20 | 253,000 | 80,000 | 500 | 92 | ⊙ | |
| 2-28 | 200,500 | 3,000 | 800 | 112 | ⊙ | |
| 3-23 | 379,500 | 157,000 | 620 | 61 | ⊙ | |
| 3-25 | 464,500 | 221,000 | 140 | Disconnect Eagle Rock | ⊠ | * |
| 3-27 | 440,000 | 207,000 | 780 | Cable Break 18 | ⊠ | * |
| 4-5 | 284,000 | 81,000 | 990 | 150-kv. bus Eagle Rock | ⊠ | * |
| 4-22 | 440,000 | 194,000 | 462 | 68 | ⊙ | |
| 4-22 | 440,000 | 190,000 | 780 | 68 | ▲ | |
| 5-1 | 366,500 | 138,000 | 2110 | 226 | ⊙ | |
| 5-16 | 391,000 | 88,000 | 650 | 15 | ▲ | |
| 5-25 | 305,000 | 126,000 | 500 | 34 | ⊙ | |
| 6-29 | 479,500 | 255,000 | 920 | 4 | ⊙ | * |
| 6-29 | 479,500 | 243,000 | 630 | 4 | ⊙ | * |
| 7-15 | 440,000 | 148,000 | 1940 | Vestal | ⊙ | |
| 7-30 | 263,000 | 52,000 | 850 | Vestal | ⊙ | |
| 8-12 | 479,500 | 218,000 | 1870 | 61 | ⊙ | |
| 9-1 | 225,500 | 60,000 | 2370 | 212 | ⊗ | |
| 10-1 | 217,500 | 37,000 | 1890 | 210 | ⊗ | |
| 10-20 | 416,500 | 150,000 | 1570 | 87 | ⊙ | |
| 10-25 | 416,500 | 117,000 | 2180 | 209 | ⊙ | |
| 11-5 | 348,500 | 47,000 | 1470 | 173 | ⊗ | |
| 11-11 | 267,500 | 10,000 | 1020 | 33 | ⊠ | * |
| 11-13 | 252,500 | 19,000 | 1940 | 170 | ⊙ | |
| 11-28 | 346,500 | 87,000 | 1330 | 91 | ⊙ | |
| 11-30 | 364,000 | 87,000 | 2780 | 238 | ⊙ | |
| 12-6 | 384,000 | 90,000 | 1620 | 169 | ⊙ | |
| 12-8 | 366,500 | 119,000 | 1620 | 140 | ⊙ | |

TABLE III—*Continued*

| Date | Connected kv-a. | Big Creek generation | Total ground amperes | Location of fault | Relay operation | System operation |
|---|---|---|---|---|---|---|
| | | | 1926—*Continued* | | | |
| 12-9 | 457,500 | 192,000 | 2100 | 233 | ⊙ | * |
| 12-11 | 440,000 | 176,000 | 1545 | 150 | ⊙ | |
| 12-17 | 427,500 | 233,000 | 1340 | 182 | ⊙ | |
| 12-26 | 298,000 | 67,000 | 1460 | 163 | ⊙ | |
| | | | 1927 | | | |
| 1-4 | .. | 97,000 | 1670 | 163 | ⊙ | |
| 2-18 | .. | 114,000 | 1320 | 32 | ⊙ | |
| 2-22 | .. | 70,000 | .. | .. | ⊙ | |
| 5-1 | .. | 141,000 | 2760 | Not found | ⊠ | |

Correct relay operation....... ⊙
Incorrect relay operation...... ⊠
Partial relay operation........ ⊗
Relays not in service............ ▲
System interruption............ *

outages has been due to 220-kv. flashovers occurring at different loads. Curve *A* shows this relation in which outages from all causes are included. In Curve *B*, only those cases in which perfect relay action was secured are included. The difference between the two curves is principally accounted for by incorrect relay operation and operation with relays not in service.

It will be seen that for loads below approximately 150,000 kw., the probability of outage is very small and has been zero when the relay operation has been perfect. The Line *C* in Fig. 7 has therefore been drawn to this value. By reference to the load and flashover curves of Fig. 7, it will be noted that during the period in which loads in excess of 150,000 kw. are transmitted, the number of flashovers is small resulting in few actual outages. For this reason, the system can economically be operated at a high rating without serious possibility of outage.

The 220-kv. system has been caused to fall out of step due to troubles originating on the 60-kv. lines, the relation between the percentage of outage and transmitted load being similar, in a general way, to the curve shown by Fig. 8. It has been found that by setting the relays on the 60-kv. system adjacent to Eagle Rock and Laguna Bell for short time tripping, the communication of these troubles to the 220-kv. system has been very greatly reduced.

## RECORDING APPARATUS

The instruments used during these tests were not designed for continuous operation, but were arranged to be cut into service whenever a ground current flowed on the 220-kv. system, due to a line-to-ground fault. The general plan of the initiating equipment of an automatic recording instrument control, is shown in Fig. 9. An induction type relay, *A*, is connected to operate whenever current flows in the neutral of the main transformer bank at the station. This relay is set so as to operate in about one-tenth second with an average value of ground current. Its contacts complete the circuits of several auxiliary relays, which connect the different elements of the recording apparatus into circuit. The contacts of one of these auxiliary relays parallel the initiating relay contacts, locking the circuit so that the instruments continue to operate even though the fault current has ceased. After a period of about 25 sec. another relay, *B*, short-circuits the holding coil of the lock-in relay, causing it to open and disconnect the apparatus. Wherever possible, the required power was taken from a source independent of the main system, so that the instruments would continue to operate even though there was a service interruption.

The various quantities measured are as follows:

1. Power into or out of station
2. Ground current
3. Bus voltage
4. Hydraulic gate opening.

The installations were made at a number of remotely separated points on the system in order to record the changes taking place at different parts of the system, and also to insure getting at least one record for each disturbance. This was rendered necessary because a short circuit at one end of the system did not always give a sufficiently large current at the other end of the system to operate a ground current relay.

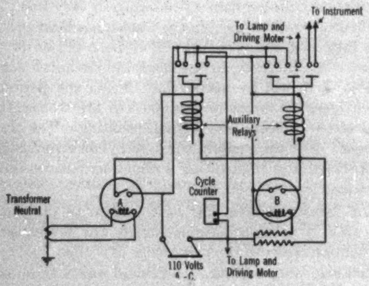

Fig. 9

### Big Creek No. 3

Two specially designed high-speed graphic wattmeters are installed in this station for recording the total station output during transients, a wattmeter being connected on the low-tension side of each of the two power transformers. As shown by Fig. 1, one records the variation in output of two of the generators, and the other measures the output of the third generator in this station. In order to record the hydraulic input to one of the generators (unit No. 3), a mechanical recording device was fastened so that it recorded the position of the turbine gates. This device was calibrated in terms of the corresponding electrical output of the generator for steady load conditions. Each of the three charts was driven by means of a synchronous motor, operated from a house generator, so that corresponding times on the three records are known.

### Vestal

A Westinghouse three-element, permanent magnet type oscillograph is installed at the Vestal substation. Two standard elements are used to measure the ground currents flowing in the two 220—150-kv. auto-transformer banks. The third element is a wattmeter and records the power input to the 50-cycle side of one of the frequency changers. This element has a natural period of about 1/20 sec., making it suitable for recording rapid fluctuations of power.

### Eagle Rock

The quantities on which measurements were made at Eagle Rock were the power to and from the Big Creek lines, the true power variations of one of the synchronous condensers, the ground current, and the voltage on the 60-kv. bus. The connections at this station were such that it was impossible to obtain a direct reading of the total incoming power, but since the transformers are paralleled on both the 220-kv. and 60-kv. sides, it was felt that sufficiently accurate power measurements would be obtained by measuring the power flow of one bank on the low-tension side, and multiplying by the ratio of the whole load to the load taken by this transformer. For this purpose a polyphase type of oscillograph wattmeter, having a natural period of about 1/20 sec., was employed. A similar wattmeter was used to record the variation in true power to one of the 30,000-kv-a. synchronous condensers. The totalized ground current of the two banks of auto-transformers was measured by means of a standard permanent magnet type of oscillograph element. An auxiliary relay was used so that after the ground current had ceased to flow, this element was transferred to measure the voltage on one of the low-tension buses. The recording apparatus at this station was arranged to operate upon the occurrence of either a 220-kv. or a 60-kv. ground. A cycle counter was used to measure the total duration of the ground current, subject to a slight error due to the time required for the initiating relay to operate.

### Laguna Bell

The output of one of the 220/60-kv. step-down transformers at Laguna Bell is measured by a high-speed graphic wattmeter of a type similar to that used at Big Creek No. 3.

### Big Creek No. 1

An additional installation was recently made at Big Creek No. 1, consisting of a single wattmeter element oscillograph, having a natural period of about 1/3000 sec., so that power variations within the cycle are recorded. This installation has been in service but a few months and has not operated frequently due to the small magnitude of the ground currents at this station.

### Typical Records

During the period in which the automatic recording apparatus has been installed, records have been obtained on about 65 flashovers. Of these, no two are exactly alike, since they involve different system setups, different loads, and different type and location of fault. Consequently from the large number of records available, it has been necessary to select a few which may be taken as typical of the different conditions that may occur in practise. The total synchronous kilovolt-amperes listed refer to the capacity connected at Big Creek, Vestal, Eagle Rock, and Laguna Bell.

At the time this flashover took place, there was no automatic protection in case a short circuit occurred on the 150-kv. bus, except that provided by the operation of the flashover suppressors; consequently the short circuit continued for several minutes. The records were taken at Big Creek No. 3, and show the combined output of generators No. 1 and No. 2, the output of, and hydraulic input to generator No. 3. The first two seconds of the record is omitted since there was little variation during this period. At about three seconds after the beginning of the short circuit, the power output at Big Creek No. 3 begins to fluctuate slightly, the rapidity of the fluctuations gradually increasing. This is probably due to the generators at Big Creek No. 1 pulling out of step with the rest of the system owing to the reduction in their field currents by the action of the flashover suppressors. After having thus pulled out of step, the mean output of Big Creek No. 1 is very small, and the loss of this generating capacity allows the system as a whole to drop in frequency. This causes the governors at Big Creek No. 3 in an attempt to regain normal frequency, to open up as shown by the record of gate opening of the No. 3 unit. Meanwhile, the arc suppressors at Big Creek No. 3 have also functioned, making the generators in that plant incapable of sustaining their load, and they also pull out of step, as evidenced by the rapid reversals of power. Each reversal in the direction of power flow means that the generators at Big Creek No. 3 have slipped a pole with respect to the rest of the system, and that they are overspeeding. The hydraulic input to the generators is then decreased by the action of the governor until normal frequency is regained. The remainder of the

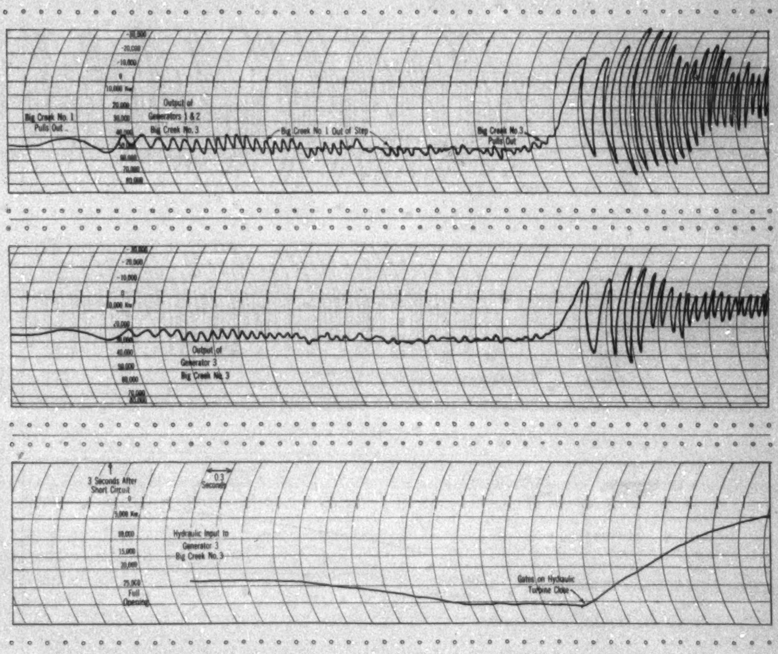

FIG. 10—(SEPTEMBER 3, 1925). FLASHOVER ON 150-KV. BUS AT BIG CREEK NO. 1. BIG CREEK GENERATION, 201,000 KW. TOTAL SYNCHRONOUS KILOVOLT-AMPERE, 424,000

charts (not shown in the illustration), shows the clearing of the short circuit and subsequent building up of load. During this period, there was considerable hunting of the governors.

This case may be taken as illustrative of the operation of the system without automatic line protection and with a large, transmitted load. At the time the short circuit occurred one of the 27-mi. lines, between Eagle Rock and Laguna Bell, was out of service, so that the balanced line relay protection could not be left in service. Therefore, the flashover suppressors at the various stations operated to reduce the machine excitations until the arc broke. Before this happened, however, the system pulled out of step owing to the reduction in voltage, and partly because the action of the governors at the Big Creek Plants had increased the total generation to meet the demand made by the short circuit. An important point brought out by these records and those of Fig. 10 is that there is no tendency for the generators in a given plant to lose synchronism with each other so long as the generators as a group remain in synchronism with the rest of the system. It will be noted, however, that when they pull out from the system, there is a tendency also to lose synchronism between generators.

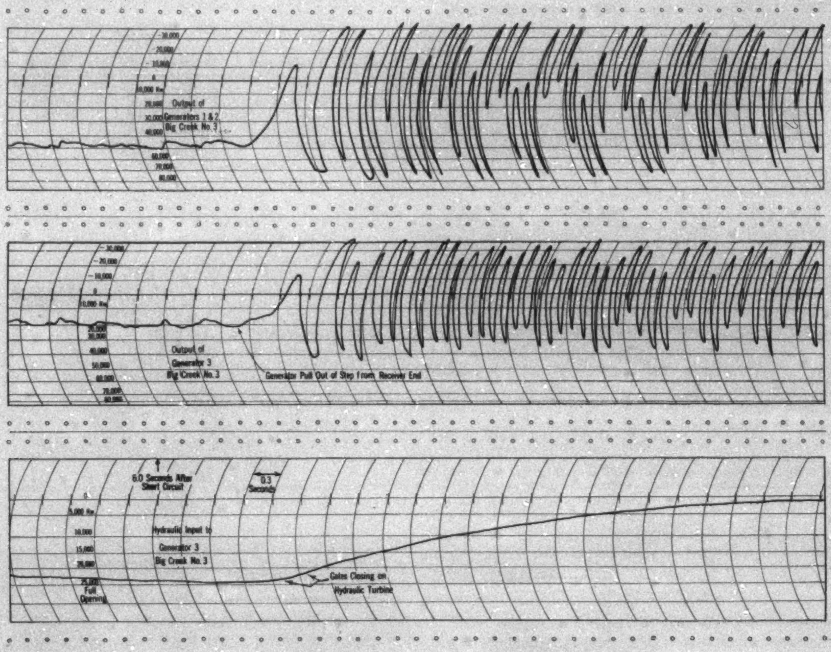

Fig. 11—(November 16, 1925). 220-kv. Flashover at Mile 212. Total Big Creek Generation, 206,000 Kw. Total Synchronous Kv-a., 439,500

Fig. 12 group of records A, B, and C, taken at Big Creek No. 3, is typical of 220-kv. flashovers not resulting in loss of synchronism. Automatic protection was in service and perfect relay operation was secured. In the cases of the first two of these flashovers, the total transmitted power was about 150,000 kw. for the two circuits, which should cause no difficulty from the stability standpoint. In the third case, however, the power generated at Big Creek was 218,000 kw. and the successful clearance of a fault at this load is excellent performance,—particularly since it involves dropping a 100-mi. section of line. Note that the high-frequency oscillations at the beginning of two of these records are mainly due to inertia of the pen mechanism.

The flashover, Fig. 13, was over a 150-kv. bushing at Eagle Rock; hence the greater part of the short-circuit current circulated through the station grounding network without the inclusion of any earth contact resistance. This low resistance type of short circuit differs from the usual type experienced on the transmission line, since practically no power is consumed by the fault itself, while the system load is probably decreased because of the greatly reduced voltage in the part of the system near the fault. The sudden loss of load allows the system frequency to increase somewhat, thus causing the governors on the Big Creek machines to cut off water as shown by the record from No. 3 unit at Big Creek No. 3. As in the case of the bus short circuit at Big Creek No. 1, the flashover suppressors were relied upon to clear the fault, which they were able to do without causing the system to pull apart, since the transmitted load was but 81,000 kw. Total synchronous kv-a., 284,000.

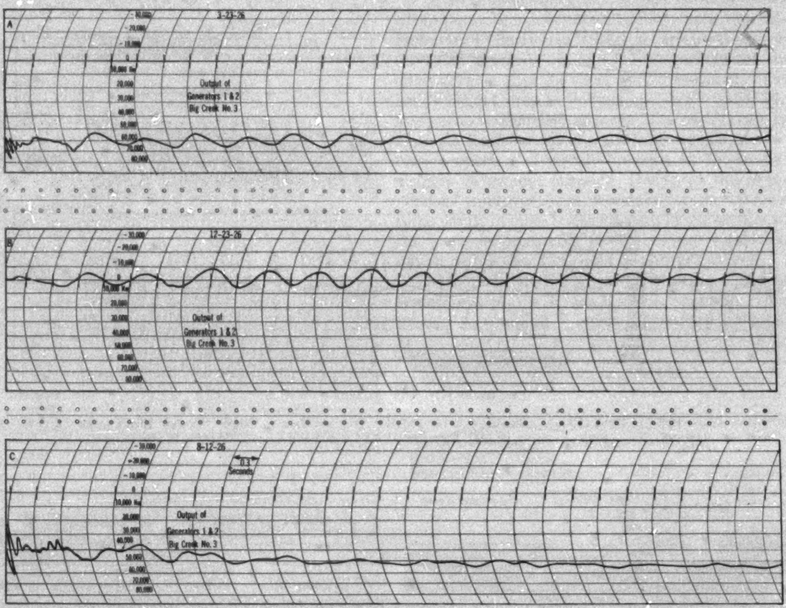

FIG. 12A—(MARCH 23, 1926). 220-KV. FLASHOVER AT MILE 61. TOTAL BIG CREEK GENERATION, 157,000 KW. TOTAL SYNCHRONOUS KV-A., 379,500
B—(DECEMBER 23, 1925). 220-KV. FLASHOVER AT MILE 8. TOTAL BIG CREEK GENERATION, 100,000 KW. TOTAL SYNCHRONOUS KV-A., 351,000
C—(AUGUST 12, 1926). 220-KV. FLASHOVER AT MILE 61. TOTAL BIG CREEK GENERATION, 218,000 KW. TOTAL SYNCHRONOUS KV-A., 479,500

Two records, Fig. 14, from Big Creek No. 3 afford an excellent illustration of the necessity for prompt isolation of a faulted line. The first flashover was caused by a hay derrick under the line, which was readily cleared by the relays and the line put back in normal service. About two hours later, in order to move the derrick, the line was made non-automatic prior to being taken out of service. But the derrick again short circuited the line while it was thus without automatic protection, and before being de-energized. It will be noted that barely three seconds elapsed before the generators pulled out of step, showing that any relay system to be adequate, must operate in a very short period of time.

In this particular case, in some unknown way, one of the wattmeter coils was inoperative, the instrument giving a single-phase reading only, which accounts for the small amount of power indicated after the short circuit was cleared. The actual amount of power at that time was close to 60,000 kw. The charts, however, serve the purpose of showing the difference in the operation with and without automatic protection.

This flashover, Fig. 15, occurred at a time when the transmitted load was fairly high, and, in addition, the fault resistance was of such a value as to cause a large amount of power to be consumed. This combination of circumstances was such as to cause loss of synchronism despite the fact that the line was relayed out correctly. The oscillographs from both Eagle Rock and Vestal showed that the generators had commenced to pull out

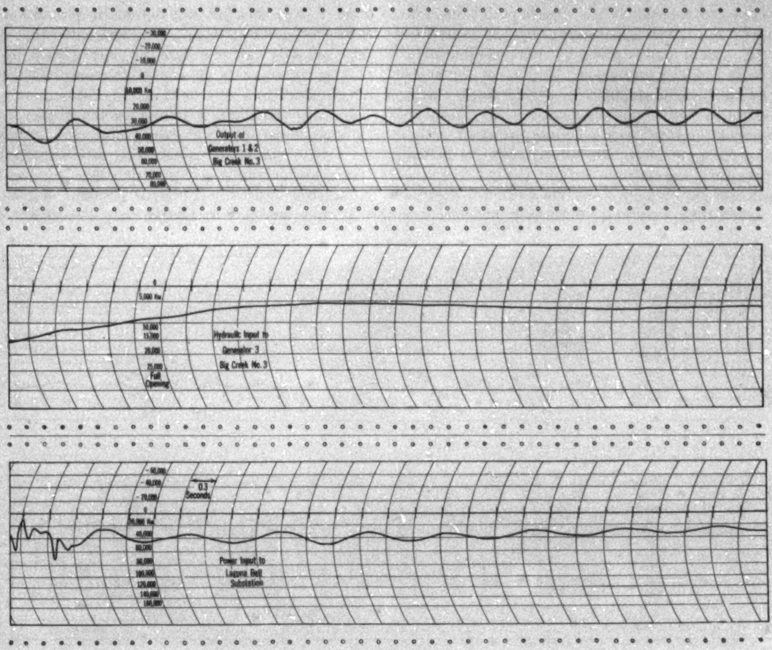

FIG. 13—(APRIL 5, 1926). FLASHOVER ON 150 KV. BUS AT EAGLE ROCK. TOTAL BIG CREEK GENERATION, 81,000 KW. TOTAL SYNCHRONOUS KV-A., 284,000

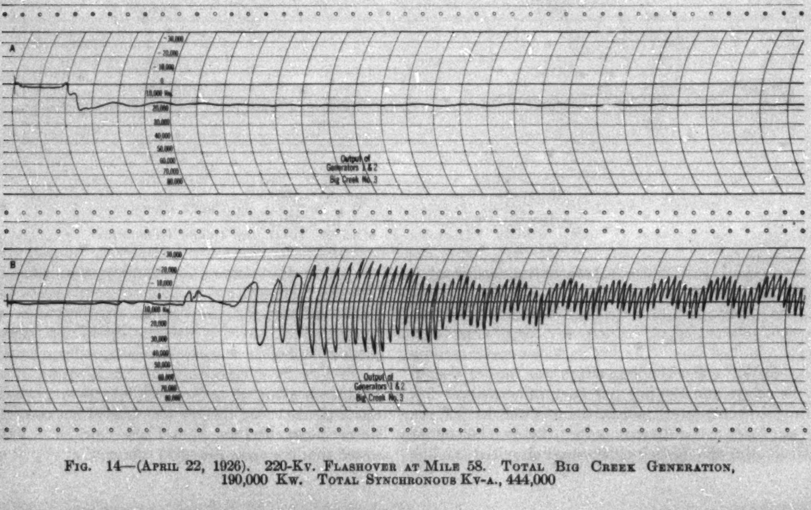

FIG. 14—(APRIL 22, 1926). 220-KV. FLASHOVER AT MILE 58. TOTAL BIG CREEK GENERATION, 190,000 KW. TOTAL SYNCHRONOUS KV-A., 444,000

of step within three-fourths second after the beginning of the flashover. (The first visible cycle on the oscillograms taken at Eagle Rock and Vestal are about 20 cycles after the start of the short circuit due to the time lag of the relays and the oscillograph lamp.) The variation in magnitude of the ground current is due to the change in voltage as the Big Creek machines shift in phase position with reference to each other and to the remainder of the system. The first visible part of the record shows that the ground current first decreases and then pulsates in amplitude indicating that the phase position of the Big Creek machines has advanced beyond the point corresponding to the maximum power limit. The enormous amount of energy consumed by this flashover is shown by the records from Laguna Bell and Eagle Rock. While the short circuit lasted (about 1.5 sec.), the power fed out of the Laguna Bell substation was over 90,000 kw. (this is the maximum the instrument could record in this direction), while the amount of power originally fed into this substation was 74,000 kw., a difference of over 164,000 kw. The original amount of power into the Eagle Rock substation was 120,000 kw., dropping to 30,000 kw. when the flashover struck. Therefore the total Big Creek power to the two receiving stations changed from 194,000 kw. in, to 60,000 kw. out, when the flashover occurred, a difference of 254,000 kw. No record was obtained of the corresponding variation in Big Creek power, but it is probable that it dropped somewhat momentarily owing to the comparatively low resistance of the fault and the high reactance of the 233-mi. of line.

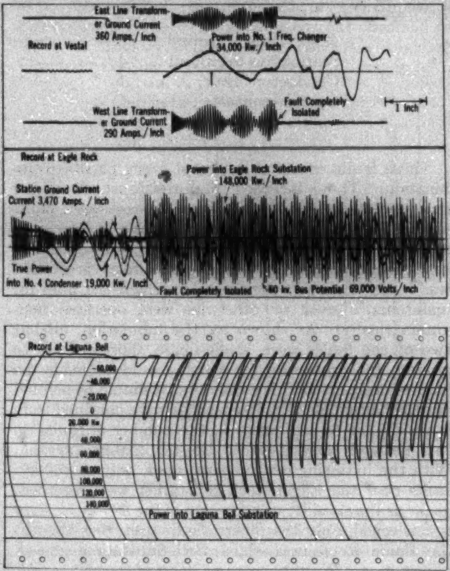

Fig. 15—(December 9, 1926.) 220-Kv. Flashover at Mile 233. Total Big Creek Generation, 192,000 Kw. Total Synchronous Kv-a., 457,500

It will be noted that a greater variation in power took place at Laguna Bell than at Eagle Rock. This is undoubtedly due to the fact that the Long Beach steam plant is more closely connected to the Laguna Bell substation so that most of the power fed to the fault from Long Beach went through Laguna Bell.

Fig. 16 shows oscillograms typical of those obtained where the system does not pull out of step with a 220-kv. flashover. The drop in voltage is very slight even while the short circuit is on, and it immediately regains its original value after the short circuit is cleared. Except for this slight drop in voltage and small power surges, there is no system disturbance. The oscillogram taken at Eagle Rock furnishes a good illustration of the successive opening of circuit breakers as shown by the changes in ground current. Owing to the line connections employed, it is necessary for the breakers at three points to open to clear a fault in the section where the flashover occurred, increasing the total time required before the fault could be entirely cleared.

The short circuit, Fig. 17, occurred on one of the 60-kv. feeders out of the Eagle Rock substation. The last breaker to completely isolate the faulted line probably opened at the point marked *A*. The Big Creek generators have already advanced beyond the point where recovery is possible, and pull-out results. In this case, the power surges back and forth between the Big Creek end of the system and the receiver end, with a surge of about plus or minus 100,000 kw. at the Eagle Rock substation. The variations at Laguna Bell are probably at least equal in magnitude, so that the total resultant power surge is probably of the order of 200,000 kw. in each direction. During this condition

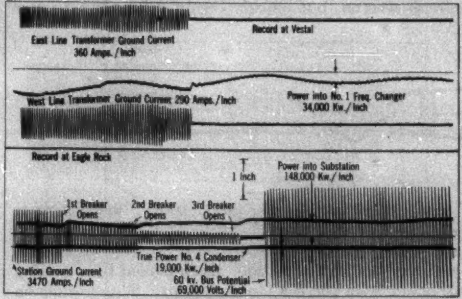

Fig. 16—(November 30, 1926). 220-Kv. Flashover at Mile 238. Total Big Creek Generation, 78,000 Kw. Total Synchronous Kv-a., 364,000

of slip between the two ends of the system, the mean power interchange is zero except for the line losses which are, in the main, supplied from the end running at the higher frequency (in this case the Big Creek machines).

The amplitude of voltage at the Eagle Rock substation varies at the slip frequency, as shown by the oscillogram. The fact that the fluctuations in synchronous condenser power occur at this same frequency shows that the condensers are maintaining synchronism with the bus to which they are connected, and are not, themselves, out of step. No instances have been recorded in which synchronous condensers have gone out of step with the station bus voltage.

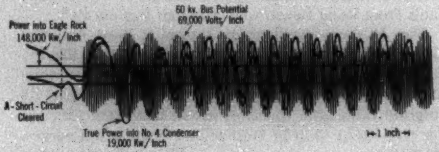

FIG 17—(JULY 31, 1926). 60-KV. SHORT CIRCUIT NEAR EAGLE ROCK. TOTAL BIG CREEK GENERATION, 205,000 KW. TOTAL SYNCHRONOUS KV-A., 439,500.

Fig. 18 gives a record included for the purpose of showing the type of the disturbance caused by a 60-kv. short circuit near McNeil substation, not resulting in loss of synchronism. The voltage on the 60-kv. bus dropped appreciably while the short circuit was on, but quickly regained its normal value with very slight fluctuations accompanied by a surging of power from the Big Creek system. The breaker on the end of the line nearest to Eagle Rock probably opened at point *A*, reducing the ground current required below that to hold the initiating relay closed. The measurement of the 60-kv. bus potential starts at this time, the voltage being about half of normal until the short circuit is completely cleared at *B*.

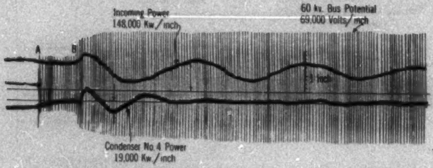

FIG. 18—(FEBRUARY 15, 1827). 60-KV. SHORT CIRCUIT NEAR MCNEIL SUBSTATION. TOTAL BIG CREEK GENERATION, 127,000 KW.

## DISCUSSION OF INDIVIDUAL FACTORS AFFECTING STABILITY

Out of a total of 65 disturbances taking place during the period that automatic recording apparatus was installed, there were practically no cases in which the system set-ups were identical or in which character of faults were the same. Consequently, it is not possible to make a direct comparison of some of the factors without the use of a certain amount of supplementary theory to place the cases on a common basis. The purpose of the following section is to isolate some of the factors affecting stability, and to analyze them individually, drawing upon the test results as much as possible.

### TYPE OF FAULTS

The 220-kv. disturbances occurring between August, 1925, and May, 1927, are as follows:

| | |
|---|---|
| 220-kv. line to ground | 59 |
| Station bus to ground | 4 |
| Conductor-break | 1 |
| Open disconnect | 1 |
| | 65 |

These faults occurred in almost every possible combination. They included high-resistance faults at many points on the 220-kv. lines, low-resistance faults on the 150-kv. buses at the ends of the line, and occurred at times of widely varying loads; also, the operations have included those in which normal relay protection was in service and other cases in which the lines for maintenance work or otherwise were operated non-automatically. As shown by the tabulation, all but two of the faults were single-phase short circuits to ground, the protection for which should be made the basis of design. In this connection, it should be pointed out that although very few records were obtained from faults on the 60-kv. network, the number of faults on this network exceed those on the 220-kv. system. With the initiating relay scheme used, only the 60-kv. faults near the Eagle Rock substation were recorded. So far as the stability of operation of the 220-kv. system is concerned, only the 60-kv. faults occurring close to the Eagle Rock or Laguna Bell Substations are of importance. For these reasons, most of the subsequent discussion will be devoted to line-to-ground faults on the 220-kv. lines, and those line-to-ground faults on the 60-kv. system, close to the receiving substations.

### LOCATION OF FAULTS

The location of a fault affects the stability of the system in two ways: (1) according to the amount of synchronous equipment and load in proximity to the fault, and (2), in so far as the local conditions affect the resistance of the fault. In order to evaluate the effect of the first, a set of curves was calculated to show the theorectical variation in the voltage, current, and power relation for faults of different resistance and locations. These curves were based on two-line operation with a single-phase ground on one line. A representative system condition was approximated by taking an average capacity in generators at the two ends of the line. Certain simplifying assumptions were made to facilitate calculations, the resistance of the lines and station ground being neglected and the generator voltages being assumed equal and in phase. The curves of Fig. 19 show the variation in total fault current against location of fault for different fault resistances. With zero fault resistance, the current varies from about 2000 amperes in the middle of a section, to about 3000 amperes at either end. As the assumed resistance of the fault is increased, the variation due to location becomes less marked until, with 100 ohms resistance, the magnitude of the current is practically independent of the location. In order to get an approximate idea of the range of fault resistances actually encountered in practise, the values of total fault current obtained for different flashovers are plotted on this diagram. Graphic recording ground ammeters are used in all of the 220-kv. generating and substations, and the sum of the readings of these ammeters was used to indicate the total fault current. The values thus obtained are not very accurate, since the ammeters were not of a type suitable for accurate measurement when the current was of short duration, and because the arithmetical rather than the vector sum was obtained. However, for purposes of comparison, it is believed that the figures are sufficiently reliable, particularly since, with so many readings to be added, the individual errors would tend to cancel out. By comparing the observed and calculated values, it will be noted that the actual fault resistance varies from about 25 to 250 ohms. The lower values of fault resistance are found near the region of the receiving end of the system, and the higher values toward the sending end. This difference can be explained by the character of the country through which the transmission lines pass. The generating stations are located in a region of rocky formation where the water is very pure and the ground resistance is high the year around. The upper part of the transmission lines also passes through this region. The middle and part of the lower section of the transmission lines passes across the San Joaquin Valley, the surface soil of which, for a large part of the year, is dry. For this reason the resistance at the point of accidental ground, such as at a transmission line tower, is quite high, even though the towers are connected by means of an overhead ground wire. The lower portion of the transmission lines is located nearer the Coast, where the soil does not become thoroughly dried out, giving a lower contact resistance. As mentioned above, the calculated curves were based on the assumption of zero ground resistance at all stations. Owing to the character of the soil at Big Creek and Vestal, the resistances at these stations are probably too high to be neglected, and there is probably a certain amount of error due to this assumption for these stations.

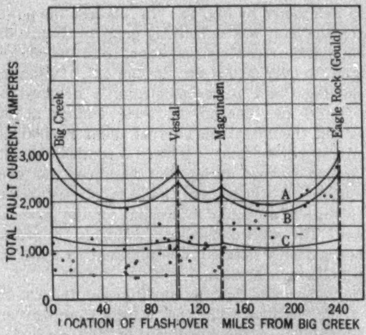

FIG. 19—VARIATION IN FAULT CURRENT WITH PHASE-TO-GROUND FLASHOVERS AT DIFFERENT LOCATIONS

A—Zero fault resistance
B—25 Ohms fault resistance
C—100 Ohms fault resistance

The flow of current through the fault resistance causes a very considerable power demand upon the system, which must be supplied by the generators at the two ends. Fig. 20 shows the calculated variation in the power consumed by a fault of 100 ohms resistance, according to its location on the system. Curve *A* shows the total power, Curve *B*, the portion supplied by the Big Creek generators, and Curve *C* that portion supplied by the generators at the receiving end of the system. From these curves, it will be noted that, with a fault close to the sending end, most of the power loss will be taken by those generators, while if the fault is located near the receiving end, the greater proportion of it is taken by the receiver generators. This division of the power increment due to the short circuit may be quite important. With a given relation between the total stored energy of rotation for the machines at the two ends of the system, the division of the power increment will determine the initial tendency toward shifting in phase position. For instance, suppose that the kinetic energy of the receiving end machinery is twice that at the sending end. For the condition for which the curves of Fig. 20 are drawn, and with the short circuit at the receiver end, 100,000 kw. of the increment of load due to the short circuit is taken by the receiver generators, and about 50,000 kw. is taken by the sending generators. Both ends of the system

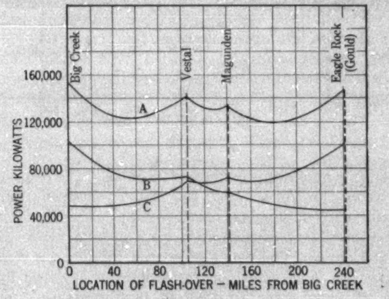

FIG. 20

will therefore slow down at the same rate, and there will be very little, if any, change in their relative phase positions; consequently, when the fault is eventually isolated, the disturbance will be slight. As the other extreme—if the short circuit occurred near the sending end, the sending generators would slow down about four times as rapidly as the receiving generators, and a considerable oscillation would result, depending upon the time in the period of oscillation at which the circuit breakers opened. No direct evidence bearing upon this point was obtained from the records, but it should be pointed out that when the Big Creek system is heavily loaded, the generating capacity at the receiver end is relatively low, making the kinetic energy of the machines at the two ends of the line of about the same order, a condition favorable to preventing large oscillations.

### FAULT RESISTANCE

As indicated by the Curves of Fig. 19, the fault current is determined very largely by the fault resistance when it is above approximately 25 ohms. The relation between the curves and the points obtained from ground current ammeter readings indicate that the fault resistances vary considerably, ranging from about 25 to 250 ohms. This value of ground resistance is very important in its effect on the system as is shown by Fig. 21 which gives the different fault resistances for phase-to-ground fault at Magunden substation. The two most important quantities from the standpoint of stability are the reduction in voltage and the increase in power demand caused by the short circuits. Between 0 and 50 ohms, the positive sequence voltage varies from 64 per cent to 80 per cent, while the power demand varies from 0 to 150,000 kw. These curves were calculated for a short circuit at Magunden, and this range of resistance is the most critical for this point. Between 50 and 100 ohms, ground resistance, the power demand due to the short circuit is practically unchanged, while the positive sequence voltage rises from 80 to 92 per cent. Although the results to the system are not so severe within this range as at the lower resistances, it is also rather a critical one, owing to the high power demand. Beyond 100 ohms, the power demand falls off rapidly, while the positive sequence voltage remains at a high value, resulting in the least shock to the system. For short circuits at other locations, the maximum power demand would be considerably increased. The commercial load on the system is also changed by the short circuits, depending upon the drop in voltage and its duration.

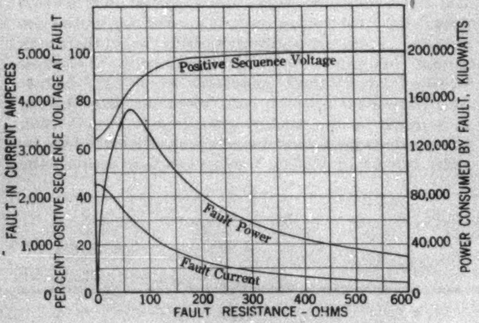

Fig. 21

The enormous amount of power consumed by a single phase ground is well brought out by the record from Laguna Bell shown by Fig. 15. In this case the power taken by the fault was sufficiently great to change the power flow at the receiving substations from 194,000 kw. flowing in, to over 60,000 kw. flowing out. Assuming that the Big Creek power momentarily dropped by about 50,000 kw., due to the lower voltage at the receiver end, the indications are that about 200,000 kw. was consumed in the fault. When it is recalled that the total ground current during this flashover was over 2000 amperes, it will be seen that a fault resistance of only 50 ohms is necessary to account for the power in question. The effect of this load, suddenly thrown on and then suddenly released, was sufficient to cause the system to lose synchronism.

It should be noted that the conditions on the 220-kv. lines of the Southern California Edison Company are very favorable from the standpoint of fault resistance, since the very great majority are over 100 ohms in resistance, while the resistances which would cause the most disturbance are considerably lower in value. This fact should be borne in mind when estimating the probable performance of other systems by comparison, because if the fault resistances are low, poor operation may result even though the system is otherwise well laid out.

Owing to the great importance of ground resistance in determining the action of the system, it may in some cases be desirable to take special precautions to keep the resistance above the critical value by using high resistance overhead ground wires, resistance grounding of transformer neutrals with full, 220-kv. class insulation or some other method; whichever may be found to be most practical in any particular case.

### RELAY OPERATION

The importance of quickly isolating a fault was discussed to some extent in connection with the flashover of April 22, and December 9, 1926. In the case of the first two flashovers, a direct comparison between a rapid relay operation and no relay operation was obtained under practically identical circumstances. With the rapid relay and switch operation (about 1.2 sec.), it was possible to cut out a 100-mi. section of line while carrying 190,000 kw., and not drop out of step. A little later when the line was made non-automatic, the system pulled out of step within three seconds after the short circuit occurred, showing that relay operation taking this length of time would not be effective for this particular set-up. In the case of the last flashover, the particular combination of high transmitted load and critical fault resistance was such that in order to have it effective, the total time for the relays and circuit breakers would have to be less than one-half second.

When a flashover occurs, the machines at the two ends of the system shift in phase position so as to conform to the new conditions. Due to their inertias, however, there is always a certain amount of oscillation. A similar tendency to shift in phase position exists when a circuit breaker opens to clear the fault, and the oscillation which this would tend to create may either add to or subtract from that already existing, with a corresponding influence on the system. There is thus an optimum time for the clearance of a given fault which is not necessarily the minimum time. Since no definite time of circuit breaker opening will be satisfactory for all cases, the best procedure is to obtain as quickly as possible an isolation of the fault. With the balance current type of relay used, it is possible to secure very rapid relay action, the minimum time being principally determined by the time required for the circuit breaker to open after being tripped.

Oscillographic measurements during a large number of flashovers give the following average times from the beginning of the short circuit for operation of circuit breakers. Straight line sections, (two breakers to completely isolate line), 0.75 sec. for first breaker to open; 1.2 sec. for last breaker. Tapped line, (three breakers to completely isolate line), 0.75 sec. for first breaker, 1.3 sec. for second breaker, and 1.7 sec. for last breaker.

### SEQUENCE OF CIRCUIT BREAKER OPERATION

In practically every relay scheme now in use, it is necessary, under some conditions, for the circuit breaker at one end of the line to open before some other relay can operate. This means that the faulty line is not opened at both ends at the same instant, but that there is a time interval between the operation of the breakers at the two ends. Due to the setting of the relays, and the adjustment of the different breakers, this effect has been observed in every case. This effect is probably advantageous from the standpoint of stability, since it reduces the size of the changes necessary to drop the heavy load due to the fault, and resume the normal load. This point is illustrated by Fig. 16; the oscillogram taken at Eagle Rock during the flashover of November 30, 1926, where three circuit breakers opened one after another to finally isolate the faulty section of line. This oscillogram shows the abrupt change at the instant the breakers opened, and the gradual readjustment between this time and the time that the next breaker opened, so that when the last breaker opened, clearing the fault, there was comparatively little change required to resume the original load, and the power oscillations are small. An interval of time between breaker operation appears desirable, but the advantage of a gradual change would probably be overbalanced if the short circuit were permitted to hang on too long. For this reason, set-ups are avoided so far as possible which would too greatly prolong the time required to isolate the faulted section of line.

### LENGTH OF LINE SECTIONS

Owing to the fact that other conditions had a greater effect, it is not possible to show from the records the influence of the length of line section on stability of operation. Other things being equal, however, it is probably safe to assume that the length of the section affects the working power limit of the line about inversely as the percentage increase in the total system impedance, (including generator and transformer reactance), caused by switching out the section.

### SYSTEM LAYOUT

The primary factors governing the location and general arrangement of generating and substations are, of course, the location of the available power and the load. However, a certain amount of freedom is permitted in the case of the larger distributing substations, and these are, in general, located so as to avoid, as much as possible, too large a concentration of power. Complicated ties between stations are also avoided, so that in case of emergency, it will be possible to separate some of the sections from the main system with a minimum of switching. The synchronous condenser capacity required for line regulation and for power factor correction is divided between the various receiving substations, and the small substations near the load. One of the advantages of this arrangement lies in reducing the number of synchronous machines which may be affected by a given short circuit, thus reducing the area affected.

### SIMULTANEITY OF BREAKER CONTACT OPENING

In some previous[4] tests reported on the action of 220-kv. breakers, it was found that in some cases, the difference in the opening of the three poles of the breaker was sometimes as much as 20 cycles, due to poor mechanical adjustment. During this interval, a ground current flowed. So far, there have been no instances shown by the oscillograms in the tests on the Edison system where there was any appreciable difference between the time of opening of the various poles of the breakers. When a 220-kv. line is opened, there is a voltage of appreciable magnitude induced in the communication circuits, but this is always of short duration, and has been satisfactorily cared for by means of saturating vacuum tubes in the telephone apparatus. The relay scheme, however, since it is of the balance current type, is not affected by residual currents of this kind.

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[4] *Practical Aspects of System Stability*, by Roy Wilkins, TRANS. A. I. E. E., Vol. XLV, 1926, p. 41.

### REACTANCE OF TRANSFORMERS AND MACHINES

Owing to their nature, the tests could not show the value of low reactance in increasing the power limit of the system, but this point has been very well established by theory, and extensions of the system are being equipped with generators and transformers having reactances lower than the usual values.

### 60-KV. SHORT CIRCUITS

On the Edison system, it has been the experience that short circuits on the 60-kv. network may be quite as detrimental to the operation of the 220-kv. lines as short circuits on the 220-kv. lines themselves if they occur close to the 220-kv. terminal substations. Fundamentally, short circuits close to terminal substations should differ but little in their effect upon the system whether they are on the 60-kv. or 220-kv. networks. Such differences as may actually exist must be due to conditions affecting the kilowatt and kilovolt-ampere demand on the system, and the duration. As pointed out in a previous section, the resistance of the majority of the faults on the 220 kv. lines is above the critical range owing to the character of the country through which these lines pass. On the 60-kv. network, the critical range of resistance is considerably lower, (approximately the ratio of the squares of the two voltages), but these lines pass through regions where it is known that the ground resistances are quite low. It appears probable, therefore, that the relatively greater severity of 60-kv. short circuits is, in part, due to the fault resistances being within the critical range. Consideration is now being given to the possibility of reducing the fault currents under phase-to-ground fault conditions by using transformers with delta connections on the 60-kv. side and possibly by removing the grounds from some of the transformer neutrals where more than one bank is located in a given station.

It was found by experience that very greatly improved operation of the 220-kv. system was obtained by reducing the time settings on the relays for the 60 kv. lines out of the Eagle Rock and Laguna Bell substations.

### GOVERNOR OPERATION

In practically every case of a flashover to ground on the 220-kv. lines, the records obtained have shown that the governors on the Big Creek generators operate to increase the input to the machines. This effect, as shown by Figs. 10 and 11, is likely to produce instability. When a flashover occurs the capacity of the line for through power transmission is reduced, owing to the drop in voltage, and when the faulty section is finally cut out, the transmission capacity is reduced still further over that originally available. Also, the oscillations in phase position of the various synchronous machines require that a flow of power in excess of the average load on the machines be available to hold them in synchronism. Any increase in the average load will cause the peaks of the power oscillations to reach higher values, and if they then exceed the transmitting capacity of the system, the generators will pull out of step from the rest of the system. This point is illustrated by Fig. 22 showing how normal governor action may increase probability of pull-out, being the transient power limit of the system being represented by the line *A*. Curve *B* is a hypothetical curve showing the variation in power output of the sending generators, and Curve *C* is the prime mover input to them. It is assumed that the added power taken by the fault causes the system as a whole to slow down, thus making the governors of the waterwheels admit more water. The peaks of the power output oscillations increase until they reach the maximum capacity of the system at which point the momentum of the generators in their oscillation cannot be absorbed by the system and they pull out. When the machines overspeed, the governors finally operate to reduce the input as shown by the continuation of Curve *C*. The remedy for this condition is to have a system of control that will partially close the waterwheel gates upon the occurrence of a major disturbance, and later, after a proper interval of time, reopen them to their previous value.

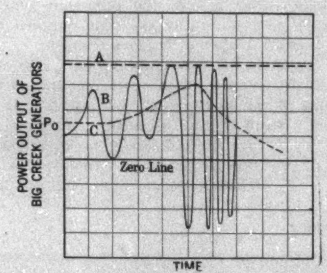

FIG. 22

The purpose of this arrangement would be to temporarily lower the input to the machines to conform to the temporarily reduced capacity of the transmission lines, and after the trouble is cleared, to gradually resume the normal load. Since at light loads it is unnecessary to take any special precautions to obtain stable operation, the relay-selecting scheme would be arranged to prevent operation unless the transmitted load was in excess of a certain predetermined value. This scheme is now being given consideration for use on the Big Creek generators. Depending upon the rate at which the gates can be closed, the use of a device of this kind should materially reduce the number of disturbances causing interruption of service, and, in the case of those which do, should facilitate the restoration of service by permitting the system to pull together more rapidly.

### REGULATION

In every case observed with the exception of that illustrated by Fig. 15, loss of synchronism, if it took place, did not occur until one second or more after the beginning of the disturbance. This shows that an appreciable time is available in which the field excitation of the synchronous machines may be increased to conform to the additional requirements. This can be accomplished only if the voltage regulator is capable of responding quickly and accurately and the exciters are able to build up in voltage rapidly. The object of a quick-response excitation system is to rapidly build up a voltage across the field winding of a synchronous machine, to provide sufficient additional magnetomotive force to neutralize the demagnetising action of the short-circuit current flowing in the armature windings. Owing to the fact that with a high resistance fault the voltage on one of the good phases may actually rise, the ordinary voltage regulator, if connected to this phase, would tend to reduce the excitation. This possibility can be overcome by the use of a regulator operated by means of a positive sequence network, and the new generators for power house No. 2-A, in addition to having a quick response system of excitation, will also have this type of regulator.

### TRANSMITTED LOAD

Whether or not a given system is able to withstand a disturbance is determined by the particular combination in which the controlling factors occur, as discussed in previous paragraphs. It is therefore impossible to place a definite numerical value on the transmission capacity of the system. However, data are available on a sufficient number of cases of flashover to permit of curves being drawn, showing the percentage of flashovers which cause outages at different loads. The curves of Fig. 8 were drawn for troubles originating on the 220-kv. system only, for the over-all operation of the system and for those cases in which perfect relay operation was secured. These curves show that the probability of an outage increases with the load being carried. The permissible operating loads depend largely upon local factors, such as frequency and time of occurrence of disturbances and perhaps even more upon how far it is justifiable to increase the cost of power in order to achieve greater reliability of service, etc. On the Edison system most of the flashovers occur in the early morning hours, when the transmitted load is low, (as shown in Fig. 7), thus making operation at high loads feasible in the daytime. In regions where lightning is responsible for most of the flashovers and the plant has storage capacity, the load may be reduced upon the approach of a storm to minimize possibility of an outage.

### CONCLUSIONS

1. There are various standards of service which may be considered. Perfect continuity is not economically feasible; the next best thing is to so reduce the effects of short circuits as to allow only momentary disturbances thus causing but slight inconvenience to the consumer.

2. It has been brought out that one of the main factors in reducing disturbance and preventing loss of synchronism between the generating and receiving ends of a transmission system is the rapidity with which relays and switches can be made to isolate any trouble. It appears very probable that by a material reduction in the time now taken, troubles could be successfully cleared when transmitting much greater amounts of power than at present, and this same high standard of service could be maintained. Looking at this from another viewpoint, systems that might be furnishing but mediocre service would have that service vastly improved in quality by such change in switch operation, provided the transmitted load were not changed. On the other hand, unless it is possible to get extremely fast switch operation, less shock is produced when one end of a faulty section is cleared a short time after the other.

3. Quick response of generator field excitation to regulation aids in maintaining synchronism by preventing, so far as possible, a drop in generator field flux. The drop in generator terminal voltage will then be determined by the generator leakage reactance, being less with low values of reactance. Similarly, low transformer leakage reactance is beneficial.

4. It also appears that a device to decrease the output from the Big Creek generators immediately upon the occurrence of a short circuit will decrease the tendency to get out of step by reducing the transmitted load. Such a device might take the form of a relay operating upon the waterwheel governors. The greater part of the load so dropped would be picked up by generators at the receiving end, so that the net effect upon the system frequency would be inconsiderable.

5. One of the most important points brought out by the tests was the relation between the severity of the disturbance and the amount of ground current upon short circuit; this demonstrates the value of adopting means to limit short circuit currents. The higher the voltage of the system, the more pronounced is this effect.

6. The amount of power that can be transmitted consistently over any given line depends upon several factors including the standard of service required, the exposure and susceptibility to outside disturbance, and the probability of these disturbances occurring at a time when maximum loads are being carried. This is well illustrated on the Southern California Edison Company's system where, due to the nature of the chief cause of short circuits, they have occurred at off-peak periods resulting in a minimum of outages.

It may be suggested that under different conditions where causes of short circuits, such as lightning, might occur at any time, it would probably be advisable to take further precautions against outage unless conditions permit of a slightly lower standard of service.

7. All the records showed that synchronous condensers at the receiving end stayed in step with each other and their bus voltage; also all Big Creek generators would stay in step together so long as the generating and receiving ends of the line stayed in step.

8. Practically all short circuits have been single phase to ground and calculations for relay design and power limit should concentrate on this condition.

9. Short circuits on either 220-kv. or lower tension lines, close to terminal substations, will cause approximately equal disturbances to the 220-kv. system.

10. When a single-phase flashover occurs, there is an increase in total system load due to the power consumed in the fault. This additional load causes a transient redistribution of power between the different synchronous machines, which is largely determined by their kinetic energy and the electrical network, causing them to shift in phase position and thus set up power oscillations or surges. The magnitude of these surges depends upon a number of factors, such as the location and resistance of fault, transmitted load, etc. The ability of the system to absorb these oscillations without loss of synchronism depends upon the electrical rigidity with which the various machines are tied together, permitting a sufficiently high synchronizing power to be developed. The amplitude of these power surges will be reduced by anything that decreases the power consumed by the short circuit. Synchronizing power will be increased by decreasing the reactance of generators and transformers and by reducing the amount of line cut out to isolate the trouble.

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## Discussion

**Svend Barfoed:** The records obtained on this system show that disturbances originate on the transmission line, and that there are only two unknown causes of flashovers in the entire period. This is a fine performance of watchfulness.

The design of transmission lines is still undergoing evolution, and better performing lines as regards flashovers can certainly be expected. It would pay to give reconsideration to the structural design and construction of transmission lines, giving regard simultaneously to mechanical and electrical features.

These latter should not be viewed separately by different departments of an organization. By reconsideration of the whole problem, the cost of construction may be greatly reduced and improved electrical characteristics obtained. This is mentioned, because it would not be justified to assume transmission line design and construction as standardized. It is certainly not possible to have perfect continuity of service, but it should be possible to approach that condition at no increased cost of design and construction.

With regard to synchronous machines it will be advisable to proceed with caution to reduce the reactance to secure increased power transmission limit. It is suggested that the degree of stability of machines between themselves for use in the same station be investigated on the test floor without line or transformers.

There also may be investigated how a machine with vanishing reactance behaves on short circuits.

**Roy Wilkins:** This paper gives for the first time definite operating data on a specific 220-kv. line.

The operating problems on the two 220-kv. lines in California are much the same. The method of attack has been somewhat different, however, due primarily to different initial system set-ups.

The Pacific Gas & Electric Company lines, (202 mi. long), are 60-cycle, with somewhat more insulation than those discussed in the paper for the above reasons (*i. e.*, original set-up).

On the Pacific Gas & Electric Company system there has been an average of four flashovers per 100 mi. of circuit per year. Of these, the greater portion, where the trouble can be definitely located, are caused by lightning and birds.

The usual flashover is relayed out and the line is put back in service as soon as the switching can be done. Some 30 or 40 per cent of the troubles can never be located.

In those comparatively rare cases of mechanical failure the line remains out until repaired. In all ordinary flashovers no repairs are needed. During the past two years two cases have occurred when both lines were out at once. In one of these one line went out due to trouble by lightning, and while it was being cut in, the second relayed out from the same cause. Both were switched in immediately and remained.

In the second case both relayed simultaneously and were switched in without further disturbance. The Pacific Gas & Electric Company lines are comparatively lightly loaded,—from 120,000 to 150,000 kw. for both lines. Their performance lies, therefore, below that part of the curve marked *C* on Fig. 7 of the paper, and a minimum of trouble due to instability is to be expected. We have, however, enough of operating data to give a very definite idea as to the relay and switching requirements:

1. It has been demonstrated that a section of line in trouble should best be cleared in the shortest possible time.

2. It is desirable to protect each line independently so that it has normal protection under all conditions.

3. Protection from phase to ground is by far the most essential, and should be set as low and as fast as possible.

4. All 220-kv. systems now in service are grounded Y-connected on the high-voltage lines so that ground protection can be satisfactorily accomplished only on the high-voltage side.

5. Low ground resistance (such as is caused by multiple grounds from ground wires grounded at every tower) will cause much greater current and therefore greater disturbance than relatively high ground resistance.

6. There is room for a vast improvement in circuit-breaker operating time, since in those relay systems where satisfactory ground relaying is secured, the greater portion of the total time is used in the oil circuit breakers, leaving very little for any differential in the relays.

The particular ground relay scheme used on the Pacific Gas & Electric Company lines has been in use on the lower voltages for about seven years with entire satisfaction; in fact, it is the only line protection which has been tried that was satisfactory.

Most of the above points have been checked independently against the data given in the paper, and they are wholly in accord with the conclusions there given. These conclusions are very worth while studying by any one at all interested in 220-kv. transmission, for on their proper use depends the success or failure of 220-kv. transmission.

**F. R. George:** I might add our experience in connection with 220-kv. lines operated by the Pacific Gas & Electric Company. Mr. Wood mentions 65 interruptions in 18 months. Covering that same period of time in the operation of Pacific Gas & Electric Company lines there was a total of 18 interruptions. In the entire period of time during which the 220-kv. system has been operating, Mr. Wood mentions 96 interruptions and we found less than 40 interruptions. These figures give an idea of the reliability of systems operated at high voltages.

As stated previously, it must be borne in mind that the system of the Pacific Gas & Electric Company is not fully loaded and the question of stability does not enter into the problem as actively as it does in the case of the Southern California Edison Company.

**Harold Michener:** The really assuring and hopeful aspect of the paper is that the authors seem to have discovered some of the reasons for the satisfactory operation of the system under the increasing demands that have been placed upon it and some of the things that can be done to make the operation still more successful under still heavier load conditions. Most of the improvements suggested can be applied either to additions to the system as they are made or to existing parts of the system,—the latter involving the greater expense.

Probably the most important improvement, the very much quicker isolation of the section of line in trouble, does not seem to be immediately available. Concentrated effort should be directed toward the shortening of relay and switch operation.

The findings and the thoughts expressed on the effect of high resistance in the fault-to-ground circuit are particularly interesting. It was not long ago that we were giving serious consideration to the best way to get a low-resistance ground connection at the foot of the towers, in order to meet the conditions of maximum overhead ground-wire protection, and to make the potential gradient from the tower members to the surrounding ground as low as possible.

Now we learn that the natural high resistance from tower to ground has been a saving feature in our transmission-line operation. This is fortunate, for in general in our territory it is easier to get a high-resistance connection between tower and ground, but, of course, precautions must be taken to avoid unreasonably high potential gradients at these points, although no group of men has agreed on a definition for "reasonableness" in this connection.

By several compromises a condition of most satisfactory operation may be obtained. These compromises will be between high resistance and low potential gradient at the tower footings, between high resistance in the ground connections at transformer neutrals and low voltage to ground from the transformer windings, and between high-resistance and low-resistance overhead ground wires.

We are in a fair way to get further information upon the effect of a low-resistance fault-to-ground circuit, although, of course, we hope the faults will not occur.

The 220-kv. lines are being extended from Laguna Bell substation to Lighthipe substation, a distance of 6½ mi., and from there to the Long Beach steam plant, a distance of 10 mi. Under the present plan the neutrals of all the transformer banks at these stations will be grounded without appreciable resistance and the ground connections at the tower footings will be of low resistance, special care having been taken to have a 4/0 copper cable attached the full length of one of the piles in each footing where piles were used and to have two standard copperweld ground rods driven in the bottom of the hole for each grillage footing. The soil conditions throughout are such that low-resistance ground connections should be expected. This means of getting low-resistance connections between tower footings and ground was installed because the lines are in a highly developed territory, and it was felt that the potential gradients between tower footings and ground, in case of an arc to the tower, should be kept to a minimum.

One ½-in. steel ground wire will be installed on each of the two single-circuit lines from Laguna Bell to Lighthipe, and one 4/0 copper ground wire will be installed on the double-circuit line from Lighthipe to Long Beach.

The work on power-system stability being done jointly by the manufacturers and the power companies is yielding very beneficial results and should be continued. In this way the whole industry learns to talk the same language.

**P. B. Garrett:** When we first installed the test equipments we used a type "MC" quick-acting relay for initiating purposes. As noted in the paper, this relay was energized from a current transformer in the grounded neutral connection. We did not expect that this relay would be caused to operate on switching operations. We did find, however, that our equipment was picking up on switch operations, due to the ground current incident to non-simultaneous operation of the three legs of the circuit breakers, which results in a momentary unbalanced condition.

To overcome these undesirable operations, we resorted to the type "CO" low-energy overload relay, set for a very short time delay, for initiation purposes. The time lag was not particularly harmful, because even with this time delay, the film is usually well under way and the record started before the important power swings occur.

One point came up in connection with the installation of the oscillograph equipment at Vestal Substation. Due to the fact that the cold resistance of the lamp filament is but one-fifteenth its hot resistance, the lamp takes a large rush of current when first energized. The lamp transformer which was supplied as a part of the oscillograph, did not have sufficient capacity to hold up the potential at the start, and the drop in applied voltage greatly increased the comparative time taken to bring the lamp to full brilliancy. By means of a special transformer of ample capacity the time lag was greatly decreased. Previously, the motor would move the film a considerable distance before the record was started.

One point might be of interest in connection with the compilation of records pertaining to flashovers. We found it necessary or very desirable to make a special form for each of the stations, this form to be filled in by the operator at the time of the disturbance; thus we are certain of obtaining complete data relative to the operating conditions at that station at the time of the system trouble. We also made a special form for use in the main office for filling in general system data, such as the system set-up, total connected kv-a., and the like.

**E. R. Stauffacher:** I should like to call attention to Fig. 1 showing the system connections on the 220-kv. system. Between Big Creek No. 3 and Vestal, 45 mi. north of Vestal, there is a new station known as Rector which is now in operation, and which is tapped across the two lines.

There will also be another line from Gould to Magunden and Magunden to Big Creek No. 3, known as the Vincent line and two lines from Laguna Bell, to a new substation known as Lighthipe and from Lighthipe to the Long Beach Steam-Plant No. 3.

The application of relay protective devices to this changed 220-kv. system, owing to the taps and combination of parallels and taps, has been quite a problem, and it is my hope some day it will be more of a clear-cut proposition, so there will be no need of as many as six or seven switches operating to clear a short circuit.

In Table II, "Causes of Flashover," information is compiled which should be of considerable interest to anyone who is contemplating a 220-kv. system, if conditions are anywhere near comparable. With only one or two exceptions the troubles have resulted in line-to-ground faults.

One thing I should like to mention particularly is the speed with which the troubles are located by the transmission department. Very rarely does it require over half a day to locate the trouble and diagnose the cause. This is certainly helpful when analyzing the operations of the protective relays and the flow of ground current at the time of the flashover.

In Table III under the heading "Total Ground Amperes," a tabulation is made, which might be interesting not only to other central-station engineers, but also to telephone engineers. I know they are quite concerned with the amount of ground current which occurs at the time of flashover. Probably by analyzing these current values, knowing what the trouble was and its location, the amperes in the ground may not prove to be as destructive as might at first be supposed. However, the conditions regarding parallels and length of exposure of course determine how much damage might result.

In addition to trouble on the 220-kv. line, the troubles on the

66-kv. line, are also of considerable concern, particularly near the major receiving stations. Due to the necessity of time-cascading with relays, the longest time on the relay settings is at the location where the heaviest 66-kv. short circuits will occur, and in the interest of system stability it is necessary to cut down the time as much as possible, even at the expense of selectivity as to relay operations in some cases.

Regarding the stability of a system it seems to me that there are four outstanding requirements for maintaining stability at the time of a severe short circuit.

First: High speed of relay operation.

Second: High speed of switch operation—and by high speed, I am not talking in fractions of a second but mean one or two cycles. This is not possible now but I hope it will be a reality in a few years.

Third: Design of the generators—particularly as regards its short-circuit-ratio characteristics.

Fourth: The application of quick-response excitation to the generating equipment.

**F. M. Gillespie:** (communicated after adjournment) It is interesting to note the high values of kilowatts (energy) consumed by phase-to-ground faults on the 220-kv. system. The writer has been severely criticized at times for even hinting that line faults could be of sufficiently high power factor to consume any appreciable amount of energy; he has heard arguments tending to prove that load is always lost as soon as short circuits occur and has been told that operators and recording instruments must be in error for indication of speed drop instead of speed rise at times of line trouble.

The particular system to which I will refer carries a hydroplant peak of about 160,000 kw., has in service close to 1400 kilometers of 80-kv. and 110-kv. circuit and over 2000 kilometers of 22-kv. and 25-kv. overhead distribution circuits. In the early days of our operation we experienced considerable trouble with hunting of the generators when high-voltage trouble occurred; after restricting the rate of opening of turbine-gate-operating servomotors conditions were so stabilized that it is only on very rare occasions that there is any visible tendency for machines to pull out of step.

In our case the retarding of gate-opening time was accomplished by insertion of suitable diaphragms in pressure-oil pipes supplying the opening end of the servomotors. At least one American turbine builder accomplishes the same result (prevents opening of turbine gates on momentary overloads) by means of an adjustable collar on the spindle of the governor head. Our first adjustment was to increase the gate-opening time for full travel to 20 sec., and after further growth of the system this was altered to 30 sec. It is found that normal load fluctuations do not cause objectionable speed variations (we carry a certain amount of suburban railway load), and the rise in speed accruing to loss of load caused by voltage dip during period of faults is considerably less than it was when the governors were adjusted to open the gates in 3 to 6 sec. for the full stroke of the servomotors.

Phase-to-phase short circuits on high-voltage lines are, in proportion to the number of phase-to-ground faults, of very rare occurrence, but sufficient of these have taken place to prove that they can also consume sufficient energy to cause frequency drop, especially if some distance away from generating stations. On our 25-kv. network faults, irrespective of whether phase-to-ground or phase-to-phase, cause increase of load at generating stations. In fact our miniature system for calculating relay settings has had to be so arranged that impedances are shown instead of simply reactances, to allow sufficient accuracy. This should be sufficient to indicate that there is enough resistance in high-voltage networks to represent considerable energy consumption under short-circuit conditions.

The experience with the 220-kv. system as described, and experience on other systems of lesser voltages leads one to question the desirability of graded insulation on high-voltage windings of transformers with the attendant solid grounding of one end of each leg to the tank, as this eliminates the possibility of inserting grounding resistance between transformer star points and earth. There seems to be no doubt that on large systems a certain amount of neutral resistance is often desirable and offers a more reliable means of controlling the dimensions of short-circuit current and energy consumption than variation of the number of transformer neutrals connected to ground. The use of a fairly high value of grounding resistance would seem to allow securing a more constant value of ground-fault current than the use of a high-resistance ground wire as with the latter the variation in value of resistance of return circuit according to the location of the fault may cause the fault current to vary over a very wide range.

I should like to inquire if the authors of the paper can trace any cases of hunting or loss of synchronism to different systems of excitation. That is, is there any special tendency for stations with individual direct-connected exciters to pull apart from stations with central excitation such as a water-wheel driven exciter set or motor-generator exciters fed by a house generator, the exciter speed and voltage in these cases being independent of the main generator speed.

**R. J. C. Wood and L. F. Hunt:** Mr. Barfoed mentions an investigation of the relative stability of machines in the same station. We did not find there was any trouble on that account. He seemed to think there might be some difficulties due to reducing the reactance.

I cannot see that that would cause the machines to fall out of step among themselves, but would rather tend to keep them together.

The showing of the Pacific Gas & Electric Company's 220-kv. system is extremely encouraging to any one who contemplates building a 220-kv. line.

Mr. Michener's remarks regarding the compromise which has to be made between (a), low-resistance grounds with a view to decreasing the potential gradient in the ground around a tower footing when a flashover occurs and (b), the apparent desirability of having a high resistance there for stability purposes, is just one more illustration that you cannot get everything out of the "Standard Handbook."

It is not quite clear whether Mr. F. R. George in his discussion refers to interruptions where load is lost, or to flashovers irrespective of whether load is lost or not.

The 65 interruptions referred to by him were 65 flashovers during 18 months; of these only 11 caused interruption to service. Of the 96 flahovers experienced during the whole time of operation, 30 actually caused interruptions; 20 of these 30 occurred when relays were out of service on account of construction and repair work. Judging from Fig. 8 as to what would have happened had the relays been in service and taking into account the load being transmitted at the time, proper relay operation would have resulted 14 times, so that the net result would have been 16 interruptions over a period of 40 months.

It is entirely probable that the 40 cases of trouble occurring on the Pacific Gas and Electric Company's line were flashovers and not all caused interruptions. It was felt only fair to emphasize the distinction between flashover and interruption as otherwise a wrong impression of the reliability of 220-kv. systems might be obtained.

We have no definite information upon the question raised by Mr. F. M. Gillespie and cannot state whether direct-connected exciter systems tend toward lessened synchronizing power to any practical extent.

**S. B. Griscom:** It is very reassuring to note from the discussions of Messrs. Wilkins and Gillespie that their independent experiences on other systems have lead to conclusions substantially in accord with those expressed in the paper. Mr. Gillespie's reference to the power factor of short circuits is particularly interesting in this regard. Despite visual evidence of frequency drop during short circuits it has apparently been difficult for him to establish the fact that short circuits, including those from phase to phase on low-tension lines may cause considerable momentary overloads. It is for the purpose of obtaining data for firmly establishing general working principles on a given system that the application of high-speed automatic recording apparatus to power systems has been advocated.

Mr. Michener's comments on fault-to-ground resistances show the number of considerations involved in determining upon the method of grounding to be employed at stations and towers for the Southern California Edison Company. The considerations are worthy of study before fixing standards of grounding procedure, since as he points out, different parts of the system may be operated under different conditions.

Mr. Stauffacher's point in regard to simplification of 220-kv. line connections is very well taken. The true measure of transmission-line cost is the cost per mile per kilowatt of permissible load transmitted. Arrangements which do not permit satisfactory line relaying or switching must necessarily reduce the permissible load that can be handled by the circuits thus increasing the cost. For this reason, a connection scheme which involves more apparatus or lines, while costing more in actual dollars, may actually cost less per kilowatt of permissible load.

Mr. Stauffacher has mentioned the application of generators of high short-circuit ratio. The stability characteristics of generators and condensers during transients is largely determined by the leakage or transient reactance of the machine, provided the field flux is maintained substantially constant. This may be accomplished by suitable combinations of machine short-circuit ratio and excitation-system response.

With reference to Mr. Gillespie's question on different systems or excitation, there have been no cases within the authors' knowledge where stations with direct-connected exciters have pulled apart from stations excited from sources independent of the main generators. In general this would not be expected since a regulator is capable of changing the exciter field flux at a faster rate than the speed is changing.

# Equipment for 220-Kv. Systems

BY J. P. JOLLYMAN[1]

Member, A. I. E. E.

***Synopsis.***—*This paper discusses the characteristics of equipment which have been found most suitable for use on 220-kv. systems or on extensive lower voltage systems. Consideration is given to general system design, governors of prime movers, generators, excitation systems, transformers, high-voltage oil circuit breakers, transmission line, and the equipment of substations.*

*The result of four years' operation of a 220-kv. system have proven it to be as reliable as a 110-kv. system. The economies of 220-kv. transmission have been realized.*

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EXPERIENCE gained from the operation of a pioneer project confirms the wisdom of the original choice of equipment or shows where improvements can be made. This paper will discuss briefly the characteristics of equipment found most suitable for a 220-kv. system in the light of four years of operation. While the statements apply particularly to 220-kv. 60-cycle systems with long lines, they also apply to lower voltage systems if due allowance is made for the differences in magnitude.

The 220-kv. transmission systems are required for three principal purposes: (1) for long distances and considerable power; (2) for short distances with large amounts of power; and (3) as a part of an ultimate network. The requirements of equipment for the three types of systems are essentially the same. The systems having long transmission lines are the most difficult to operate on account of the very large charging kv-as. that must be supplied. The system with large power but with short transmission is less difficult to operate but imposes very severe duty on the oil circuit breakers.

## GENERAL SYSTEM DESIGN

When planning a transmission system for 220-kv. operation, the entire system with its connected equipment must be considered as a whole or as a part of the whole of the ultimate system. The sections of transmission circuits which must be handled as a unit have to be determined, since the kv-a. required to bring these sections of transmission to normal voltage decides the size of generating units and of synchronous condenser units.

Experience has very definitely established the necessity for operating 220-kv. transmissions as well as lower-voltage transmissions containing a considerable amount of transmission mileage with the transformer neutrals solidly grounded not only at the generating stations but also at all substations. All transformer banks should be equipped with delta-connected windings for the purpose of stabilizing the relation between the separate phases as well as improving relay operation. In the case of transformers at generating stations, the delta winding becomes the low-voltage winding of the transformer bank. In the case of transformers at substations, the delta windings can frequently be used to supply the necessary synchronous condensers.

Due consideration must be given to the supply of charging current, and this supply must take into account the fact that the generators, when carrying load, must operate at a high power factor if stability is to be maintained. These requirements will generally make it necessary to operate a high-voltage transmission with a drop in voltage in the direction of the flow of power. The effect of this operation will be to necessitate supply of charging current from the receiving end of the line, leaving the generators free to operate at a high power factor.

Under heavy loads, it is possible to supply sufficient boost at the receiving end of the transmission section to bring its voltage to an equality with the sending end of the same section without causing a leading current in the generators at the sending end. In very extensive networks where the flow of power may be reversed, operation at the same voltage at all points may become necessary.

Should this be essential, definite provision for a supply of charging current at some of the generating stations will have to be made.

Some flashovers of line insulators seem inevitable. Interference from external sources cannot always be avoided, nor has any insulation yet been found which will withstand the effects of all kinds of lightning. When a failure does occur, the section of line involved in the failure must be disconnected from the system with the least possible delay. While the arc resulting from a flashover may be extinguished by dropping the system voltage, this operation will nearly always result in the loss of synchronism between the generating stations and the load. It therefore seems better to cut out the section of line on which trouble has occurred.

Experience shows that this can be done in the majority of cases without loss of load, provided the sections of line remaining in service have sufficient capacity to carry the total load. To disconnect a section of line on which trouble has occurred requires the use of automatic relays. Excellent satisfaction has been experienced with the use of directional overload and directional residual relays. It is possible to connect the directional residual relays to the system in such a manner as to secure inverse time operation. With

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[1] Pacific Gas & Electric Co., San Francisco, Calif.

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such a system of connections, it has been found possible to relay out one of two parallel lines even though the trouble was within one per cent of the total distance from one end of the section. To attain this result from the balanced system of relays is extremely difficult, if not impossible.

### GENERATING STATIONS

The prime movers of generators employed on high-voltage systems will usually be steam turbines or waterwheels of the reaction or impulse type. The only special requirement of prime movers for such systems is that their governors should hold the speed very close to normal without hunting at no-load. This requirement must be met if quick operating is to be attained.

In the case of certain types of hydroelectric plants where pulsations in penstock pressures tend to cause the waterwheels to hunt when running at no-load, this is not an easy requirement to meet. The use of a load limiting device on the governors which will permit a convenient adjustment of the output of the prime movers has been found very useful. Especially in hydroelectric plants it is frequently desirable to limit the output of many of the units and permit only a few units to govern. The load limit device permits of such operation in the most advantageous manner.

The generating units may be called upon to build up the voltage on transmission line sections for the purpose of tests or for the purpose of bringing up a section to put it in service. In either event the generator must be first connected to the line with little or no field current. The fact that no terminal voltage, or a very low terminal voltage, would exist on the generator prior to the time the line is brought to full voltage prohibits the use of electric drive governors. The later types of mechanical drive for governors have proved so satisfactory that there seems little reason to desire the electric form of drive.

From the standpoint of the function which they must serve in connection with the operation of this system, generating units connected to high-voltage systems fall into two classes: (1) Tho seunits which must be of sufficient capacity to handle designated sections of the transmission lines (such units will generally be of fairly large size); and (2) smaller units having insufficient capacity to handle any part of the high-voltage system whose function is merely to feed in a certain amount of power but which must be cleared from the system in case of trouble or in case of line test.

The larger or control units should have fairly high short circuit ratios so that they may have good stability during system disturbances and be able to carry charging kv-a. at least equal to rated capacity without exceeding rated terminal voltage. Such generators should also stand occasional overvoltages of the order of 50 per cent since switching operations may occur at any time which will result in high over-voltage.

A smaller generator should have a sufficiently high short-circuit ratio for stable operation and should have the ability to operate with considerable overvoltage at least for brief periods.

### EXCITATION SYSTEMS

Excitation systems for generators supplying high-voltage lines must be automatic as to their voltage control and must operate with the highest practicable speed, especially in a case where direct-connected exciters are used. If this is not done, the generator voltage will vary far too much with the changes in power factor resultant from the changes that occur, especially in case of line trouble. The automatic voltage regulators should be direct-connected to the generators and not to the station bus. The generators are thus protected from protracted overvoltage in the event of their being tripped off the bus.

The use of direct-connected exciters, which is desirable from nearly every standpoint, presents an additional problem because of their being affected by generator speed. Hence, on such an increase of generator speed as will be occasioned by sudden loss of load, the terminal voltage of the generator tends to increase with the square of the increase of speed. To avoid this compounding effect, the automatic control of the excitation system must have a very quick response.

Sudden loss of full load, with large hydroelectric units driven by reaction turbines, results in a speed increase of the order of 30 per cent. In the case of impulse wheels, this speed increase can be reduced somewhat provided governor action in less than two sec. is permissible. With excitation systems having fairly high speed response, it has been found possible to hold the generator terminal voltage to a rise which is not greater than the per cent rise in speed.

In order that each main generating unit may be as independent as possible, the use of direct-connected exciters, with a voltage regulator for each unit, has been found very satisfactory.

### TRANSFORMERS

Modern high-voltage transformers have given very good service in high-voltage systems. The reactance of these transformers should be kept as low as can be reasonably obtained. If this is not done, the transformers will contribute to bad voltage regulation of the system especially when lines are being tested or sections of lines placed in service.

The short-circuit current through transformers connected to long distance hydroelectric systems tends to be limited by the generating capacity or the line impedance rather than by transformer impedance. It does not seem necessary to introduce any additional reactance in the transformers for such systems to protect them from damage from short circuits.

In the case of transformers fed from large steam turbine generating units, great care must be exercised to provide for their safety under a short circuit on account of the higher momentary short-circuit currents of steam turbine units as compared with water-wheel units. Like the generators, the transformers must stand considerable overvoltage. However, as transformers designed for an induced potential test of 2.73 times normal voltage have given perfect results on solidly grounded neutral systems, it does not appear necessary that for such systems they should be designed to stand a higher test voltage.

For generating station transformers with low voltages of 11 kv. or 13 kv., the core-type transformer has much to commend it from the standpoint of the simple form of major insulation. For auto-transformers or for transformers having high low-tension voltages the shell type of design permits of a better control of the characteristics of the transformers.

## HIGH-VOLTAGE OIL CIRCUIT BREAKERS

To lessen the effects of short circuit or grounds on high-voltage system and to reduce the amount of energy which must be dissipated within a high-voltage oil circuit breaker, such circuit breakers should operate with very high speed. The total time of operation for an opening stroke should be well under one-half second. Any longer time than this may result in serious effects in the transmission network.

Admittedly, this requirement is a difficult one to meet. However, it is agreed that the problem of attaining still higher operating speeds in large circuit breakers is one of the most important confronting the transmission industry. In times of peace, some of the mechanical skill which has been applied to the design of instruments of warfare could very profitably be devoted to the refinement of the mechanical design of oil circuit breakers.

An incidental requirement for the satisfactory operation of an oil circuit breaker is that it must be mechanically trip free. This trip-free function must be so arranged that a minimum time is consumed between the instant that a short circuit is encountered and the instant that the circuit breaker will be opened.

With the establishment of 220-kv. systems with considerable lengths of line, leading currents of some magnitude are made available and it has been found that the rupture of such currents creates lengths of arcs within oil circuit breakers very much greater per ampere of leading current than per ampere of short-circuit current of a lagging power factor. In fact, the length of arc drawn within oil circuit breakers is of the same order of magnitude for the charging current of a 200-mi. section of 220-kv. line as for a short circuit close to the oil circuit breaker.

## TRANSMISSION LINE

The transmission line as a mechanical structure has given excellent service. Reasonable factors of safety were employed on the structures, the design of which is subjected to test to destruction. Low stringing tensions were employed for the conductors, primarily for economy in cost of the towers. No trouble has been encountered from conductor vibration. It is felt that the low stringing tensions contribute to this desirable result.

No difficulty or evidence of undue depreciation has been encountered in the insulators used. The mechanical loads imposed on the insulators are rather moderate. With a material of the character of porcelain, it seems wise to proceed with caution in regard to the loading imposed. While high strengths have been developed for test load conditions in comparatively small porcelain suspension insulators, it is felt that the best way to employ this strength is to increase the factor of safety rather than to increase the initial load on such units.

In the case of the system with which the writer is familiar, accumulated evidence appears to point very directly toward the benefits to be derived from the use of an amount of line insulation which gives high flashover values. In the case of 110-kv. lines it is definitely known that even a comparatively small increase in the length of insulator strings secures a marked reduction in the number of the cases of flashovers experienced. There seems no reason to doubt that the same will be true in higher-voltage systems. This statement is made for a territory where lightning is a comparatively minor factor. In territory where lightning is a frequent source of trouble, caution should be used to see that the flashover value of the line insulation is not so high as to cause failures in the insulation of switches of transformers. However, if there is any question of the ability of the apparatus to stand the flashover voltages developed by the line insulation, it would be better to increase the breakdown values of the apparatus insulation rather than to decrease the flashover values of the line insulation.

One of the most trying problems, and one concerning which there is no certain solution in sight, is the question of maintaining sufficient insulation in sections where conditions permit of excessive surface leakage of line insulators. This problem is particularly acute in California in districts close to the ocean where the combination of the westerly trade winds and the ocean fogs results in a rapid accumulation of dirt on the insulator surfaces which are frequently wet by the fogs. The only method thus far discovered for securing high continuity of service in these sections is by artificial cleaning of the insulators during the months in which rain does not fall.

Some device for suppressing corona discharge of the conductor and wire clamps at the insulators appears highly desirable, since such a device tends to offset the distortion of electrostatic field at the points of support. It is not so certain that devices are required to improve the grading of the voltage impressed on the several units of long suspension strings. Apparently, as good results have been obtained in operation with devices for suppressing corona that have little or no grading effect as have been obtained with devices for suppressing corona that are arranged for considerable grading effect.

An insulator string is most likely to fail when wet by a fog. At this time the distribution of voltage is undoubtedly determined by leakage currents rather than by the condenser effect of the unit. Obviously, grading devices are ineffective at the very time an insulator string is most likely to fail.

It is believed that the conductors of high-voltage circuits should be transposed so that the electrical characteristics of each phase wire may be as nearly like the characteristics of the other phase wires as possible. Additional reasons for transposing each circuit occur where two parallel circuits are used. In this case, transpositions should be so arranged that one circuit is transposed with respect to the other. In this way, inductive effects of trouble on one circuit upon the other circuit are minimized.

The use of double-circuit towers appears to be permissible where no sleet is encountered. This construction is a very distinct economy compared with the use of two separate single-circuit lines.

### SUBSTATIONS

The requirements of equipment for substations are similar to those of generating stations in practically all respects. The main transformers may be auto-transformers if the ratio of voltage transformation is not more than 2:1. In such transformers, delta-connected windings should be employed and may be used for synchronous operation if desired.

Synchronous condensers must work over the complete range from full boost to as much buck as they are designed to supply. Some economy of cost can be had if the bucking capacity of the synchronous condensers is not more than 60 per cent of their boosting capacity.

Where very long sections of transmission line must be handled, it will be found necessary to employ a synchronous condenser in addition to a large generator in order to supply the charging kv-a. for bringing the circuit up to full voltage. For this operation, the condenser may be attached to the circuit with little or no field excitation and the generator may be used to secure the desired voltage.

In certain substations, control being a number of outgoing circuits which it would be desirable to test by building up rather than by cutting into the bus, the use of a driving motor on a synchronous condenser, permitting the operation of the condenser as a generating unit, will be found very convenient. At first thought it seems best to make these driving motors of the induction type. However, it is believed that a synchronous drive motor will serve the purpose equally well and will have the advantage of operating with a greater air-gap. The synchronous driving motor should have the same speed as the synchronous condenser. The unit should be started in the usual way, using the main condenser.

When the main condenser has reached synchronism, the driving motor can be cut in to carry the unit while the main condenser is being used as a generator for test purposes.

A flexible switching scheme should be used for main substations so that the various operations may be conducted with the utmost dispatch. The arrangement should be such that access to any oil switch may be had without material loss of switching flexibility because oil switches require considerable maintenance.

In closing, it may be said that four years of operation have proved that a 220-kv. system can be expected to give as good service as can be had from a 110-kv. system. With four times the kilowatt capacity at approximately twice the cost per mile the 220-kv. system affords a very distinct economy in the cost of transmission where the amount of power is sufficient to justify the use of the higher voltage.

The success that has attended the operation of the pioneer 220-kv. systems proves that the economies of these systems can be realized and can be applied to increasing the transmission radius at a given cost or for decreasing the cost for a shorter radius.

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## Discussion

**Harold Michener:** Mr. Jollyman speaks of the dirt and the salt accumulation on insulators. Our experiences indicate that the only way to maintain satisfactory service is to clean the insulators as frequently as necessary, that frequency being determined by a study of local conditions.

**R. J. C. Wood:** An insulator string is most likely to fail when wet by a fog. At this time the distribution of voltage is undoubtedly determined by leakage currents rather than by the condenser effect of the unit.

That, I believe, is entirely true where there is not much lightning trouble; but the effect of grading a string is to increase the lightning flashover value.

This grading should be more valuable to those building lines in the East and mountainous parts, where lightning is more frequent than it is here.

# Static Stability Limits and the Intermediate Condenser Station

BY C. F. WAGNER*
Associate, A. I. E. E.
and
R D. EVANS*
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THE development in power transmission has been in the direction of delivering increased amounts of power per circuit over greater distances. This trend raises two fundamentally important questions:

1. What constitute the output limitations of the alternating current system of power transmission, and
2. How close to these limits is it feasible to operate transmission systems?

During the past few years, investigations have been under way to find the answers to these questions. Stability has been recognized as the outstanding output limitation of power systems utilizing synchronous machines of the types now in use. There have been a number of proposals for increasing the stability limits of power systems. The use of lower system frequency and the reduction of the series impedance of the system are obviously of value in increasing the stability limits. Recently, the latter method, by decreasing the machine impedance, has been adopted in a number of transmission undertakings. Of course, raising the transmission voltage has been considered, but it is relatively expensive and does not avoid the "distance limitation" in lines approaching the quarter wave resonant length. This effect becomes important for distances considerably below the theoretical value because of the impedance of terminal equipment.

One proposal of greater promise than any of those mentioned in the previous paragraph is the use of the intermediate synchronous condenser station. In 1921 Mr. F. G. Baum† presented an important paper devoting a considerable part of it to the use of intermediate condenser stations, which he advocated as a method of making technically feasible the transmission of 60-cycle power to substantially unlimited distances.

Since the early proposals to utilize the intermediate condenser station to increase the stability limits of transmission systems, the entire subject has received a very great deal of attention before the Institute and in the technical press. During 1924, Messrs. Evans and Bergvall‡ presented the results of tests made during the previous year, giving experimental verification of the increases in stability limits possible by the intermediate condenser. The tests were made on a miniature power system and showed improvements as great as 42 per cent. In the bibliography is listed a number of technical papers published in America dealing with the intermediate condenser station problem.

The best physical explanation of the elements entering into the stability problem in general and the intermediate condenser station problem in particular is obtained from a study of the mechanical analogy suggested by Mr. S. B. Griscom*. The mechanical model was first built by Mr. C. F. Wagner and used by him for the demonstration of the stability phenomena during the year 1926. In reality, the model is a synchronous mechanical transmission system used to simulate the action of a synchronous electrical transmission system.

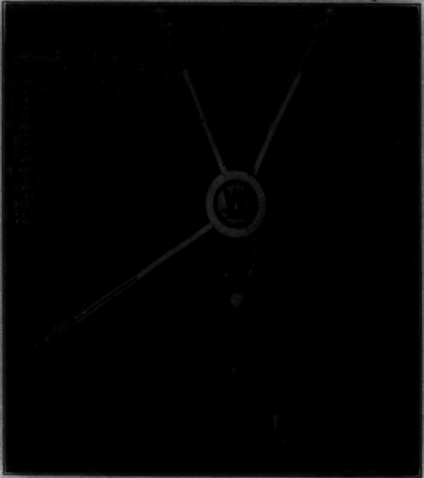

FIG. 1—MECHANICAL MODEL FOR TWO MACHINES

The mechanical model as applied to a simple system involving a generator, reactance line, and synchronous motor is illustrated in Fig. 1. The model consists essentially of two rotatable members mounted on a common shaft. Each member consists of a small flywheel to which a lever arm is attached. Each member is provided with cords so arranged that downward forces tend to rotate the members in opposite directions tending to separate the lever arms, this action being opposed by a spring connecting them. The points in the analogy are indicated by the table accompanying Fig. 1.

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*Both of Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

†Bibliography, Item 1.

‡Bibliography, Item 3.

*Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., September 13-16, 1927.*

*Bibliography, Item 10.

Such a mechanical system represents quite faithfully from the standpoint of stability all the essential phenomena that take place on a simple electric power transmission system. When the load is in excess of that required to produce a displacement of 90 deg. between the two lever arms under steady load conditions, the system pulls out of step, simulating the pull-out of an electrical system. Incidentally, it may be mentioned that when the resistance in the electrical system is neglected the pull-out takes place at the same angle on the two systems.

The power limits of the mechanical system can be increased by using a stronger spring, which corresponds to lower series impedance in the electrical system, and also by using longer lever arms which correspond to higher transmission voltages. However, probably the easiest way of increasing the power limit of this mechanical system is to insert a mechanical prop at an intermediate point. If a rigid prop is located at the mid-point, the mechanical system can transmit twice as much power as before. The electrical equivalent is a synchronous condenser of zero impedance. Ordinary synchronous condensers may be represented by the introduction of a spring between the extremity of a movable arm representing the internal voltage of the condenser and the point on the spring corresponding to the location of the condenser as indicated in Fig. 2.

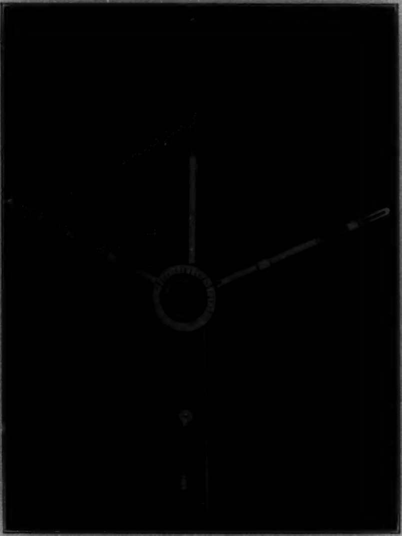

FIG. 2—MECHANICAL MODEL INCLUDING INTERMEDIATE CONDENSER

It is not feasible to go into a detailed explanation of the performance of the mechanical model for steady state or transient conditions. This description of the mechanical model has been given here to assist in a physical interpretation of the analytical methods presented in the paper. Further information may be obtained by referring to the article by Mr. Griscom.

The present paper incorporates the results of investigations to determine the stability characteristics of systems with intermediate condensers. These investigations necessarily have included work on the general stability problem of systems involving three or more sources of synchronous e. m. f. In fact, the present study is concerned chiefly with an analytical investigation of the static limits of network power systems disclosing methods applicable to the intermediate condenser station problem.

It is desirable at the outset to point out the limitations of the investigations. The present paper is confined to static limits. Static limits are important because they may be approached under emergency conditions even though the system is designed to operate well below these limits normally. It is recognized that stability limits under transient conditions occur for smaller values of transmitted power. The authors presented a step-by-step method† applicable for the determination of the transient limits of transmission systems including intermediate condensers. It may be pointed out that static limits are best investigated by the application of a criterion obtained on the basis of small transients. In regard to the intermediate condenser station problem, specifically, the nature of the problem lends itself well to a general investigation from the standpoint of static limits, whereas it does not lend itself to a general investigation of transient limits. Two of our colleagues, Messrs. R. C. Bergvall and P. H. Robinson will present in the near future a paper describing the application of the mechanical model to the solution of stability problems of net-work power systems. The authors hold the opinion that this method offers real promise for the solution of practical problems involving the intermediate condenser station as well as the problems of the closely connected power system.

The general outline of the paper is as follows:

1. General representation of systems.
2. Discussion of the assumptions involved.
3. Stability limit of the two-synchronous-machine case.
4. Calculation of the stability limits of straight-away transmission systems.
5. Static limit of the three-synchronous-machine case including a study of one intermediate condenser station.
6. Stability limits of the four-synchronous-machine case.
7. Calculation of power limits with one and two intermediate condenser stations.

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†Bibliography, Item 12.

## GENERAL REPRESENTATION OF SYSTEMS

In general, the solution of any physical problem is reached by the solution of equations, the number of these equations being equal to the number of unknown quantities in the problem. This is also true for a-c. networks with fixed constants. Because of the linear nature of the first and second laws of Kirchhoff, which alone are necessary for a solution, the simultaneous equations are always linear, with constant coefficients. The solution for the terminal currents in terms of the terminal voltages of an $n$ terminal network can always be reduced to the following form*

$$\left.\begin{aligned} \mathbf{I}_a &= \mathbf{Y}_{aa}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b - \mathbf{Y}_{ac}\,\mathbf{E}_c \;.\;.\;.\;.\;.\; - \mathbf{Y}_{an}\,\mathbf{E}_n \\ \mathbf{I}_b &= -\,\mathbf{Y}_{ba}\,\mathbf{E}_a + \mathbf{Y}_{bb}\,\mathbf{E}_b - \mathbf{Y}_{bc}\,\mathbf{E}_c \;.\;.\;.\;.\;.\; - \mathbf{Y}_{bn}\,\mathbf{E}_n \\ \mathbf{I}_n &= -\,\mathbf{Y}_{na}\,\mathbf{E}_a - \mathbf{Y}_{nb}\,\mathbf{E}_b - \mathbf{Y}_{nc}\,\mathbf{E}_c \;.\;.\;.\;.\; + \mathbf{Y}_{nn}\,\mathbf{E}_n \end{aligned}\right\} \quad (1)$$

in which the coefficients $\mathbf{Y}_{aa}$, $\mathbf{Y}_{bb}$ . . . . $\mathbf{Y}_{nn}$ are termed self admittances, and the coefficients $\mathbf{Y}_{ab}$, $\mathbf{Y}_{mn}$, etc., are termed mutual admittances. It can be shown that $\mathbf{Y}_{mn}$ is equal to $\mathbf{Y}_{nm}$. The network is then completely defined as far so the terminal conditions are concerned by $n$ self admittances and $\frac{n}{2}\ (n - 1)$ mutual admittances. A two terminal network will reduce to a network of two self admittances and one mutual admittance, a three-terminal network will reduce to a network of three self admittances, and three mutual admittances. The physical significance of these notions may be illustrated by considering in more detail a three terminal network. The equations for this case are

$$\left.\begin{aligned} \mathbf{I}_a &= \mathbf{Y}_{aa}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b - \mathbf{Y}_{ca}\,\mathbf{E}_c \\ \mathbf{I}_b &= -\,\mathbf{Y}_{ab}\,\mathbf{E}_a + \mathbf{Y}_{bb}\,\mathbf{E}_b - \mathbf{Y}_{bc}\,\mathbf{E}_c \\ \mathbf{I}_c &= -\,\mathbf{Y}_{ca}\,\mathbf{E}_a - \mathbf{Y}_{bc}\,\mathbf{E}_b + \mathbf{Y}_{cc}\,\mathbf{E}_c \end{aligned}\right\} \quad (2)$$

Now, referring to Fig. 3 it will be seen that the above equations represent the solution of the network indicated. The truth of this statement can be shown as follows:

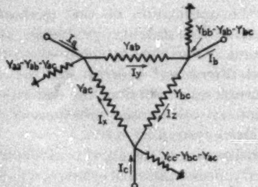

FIG. 3—ADMITTANCE DIAGRAM REPRESENTING GENERAL CASE FOR A THREE-TERMINAL NETWORK

Since

$$\mathbf{E}_a = \mathbf{E}_b + \frac{1}{\mathbf{Y}_{ab}}\,I_x$$

then

$$\mathbf{I}_x = +\,\mathbf{Y}_{ab}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b$$

Similarly

$$\mathbf{I}_x = +\,\mathbf{Y}_{ca}\,\mathbf{E}_c - \mathbf{Y}_{ca}\,\mathbf{E}_a$$

Equating the currents at the junction $a$

$$\begin{aligned} \mathbf{I}_a = (\mathbf{Y}_{aa} - \mathbf{Y}_{ab} - \mathbf{Y}_{ca})\,\mathbf{E}_a &+ (\mathbf{Y}_{ab}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b) \\ &- (\mathbf{Y}_{ca}\,\mathbf{E}_c - \mathbf{Y}_{ca}\,\mathbf{E}_a) \\ = \mathbf{Y}_{aa}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b - \mathbf{Y}_{ca}\,\mathbf{E}_c & \end{aligned}$$

This is identical to the equation defining $\mathbf{I}_a$. The expressions for $\mathbf{I}_b$ and $\mathbf{I}_c$ can be proved in a similar manner.

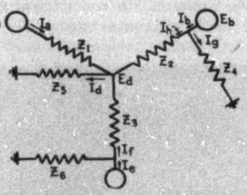

FIG. 4—DIAGRAM REPRESENTING PARTICULARLY CASE OF A THREE-TERMINAL NETWORK

To insure a thorough understanding of the significance of these constants, consider the particular example of a three terminal network, shown in Fig. 4. This represents three generators feeding the load represented by $\mathbf{Z}_5$ through impedances. In addition, two of the machines have loads taken off their terminals. The equations for the network of Fig. 4 may be written as follows:

$$\mathbf{I}_a = \frac{1}{\mathbf{Z}_1}\,\mathbf{E}_a - \frac{1}{\mathbf{Z}_1}\,\mathbf{E}_d = \mathbf{Y}_1\,\mathbf{E}_a - \mathbf{Y}_1\,\mathbf{E}_d$$

$$\mathbf{I}_h = \frac{1}{\mathbf{Z}_2}\,\mathbf{E}_b - \frac{1}{\mathbf{Z}_2}\,\mathbf{E}_d = \mathbf{Y}_2\,\mathbf{E}_b - \mathbf{Y}_2\,\mathbf{E}_d$$

$$\mathbf{I}_f = \frac{1}{\mathbf{Z}_3}\,\mathbf{E}_c - \frac{1}{\mathbf{Z}_3}\,\mathbf{E}_d = \mathbf{Y}_3\,\mathbf{E}_c - \mathbf{Y}_3\,\mathbf{E}_d$$

$$\mathbf{I}_d = \qquad + \frac{1}{\mathbf{Z}_5}\,\mathbf{E}_d = \qquad \mathbf{Y}_5\,\mathbf{E}_d$$

. . . . . . . . . . . . . . . .

Summing the currents at the junction point

$$\mathbf{I}_a + \mathbf{I}_h + \mathbf{I}_f - \mathbf{I}_d = 0$$

Substituting and solving for $\mathbf{E}_d$

$$\mathbf{E}_d = \frac{\mathbf{Y}_1\,\mathbf{E}_a + \mathbf{Y}_2\,\mathbf{E}_b + \mathbf{Y}_3\,\mathbf{E}_c}{\mathbf{Y}_1 + \mathbf{Y}_2 + \mathbf{Y}_3 + \mathbf{Y}_5}$$

From which

$$\mathbf{I}_a = \mathbf{Y}_1\,\mathbf{E}_a - \mathbf{Y}_1\,\frac{\mathbf{Y}_1\,\mathbf{E}_a + \mathbf{Y}_2\,\mathbf{E}_b + \mathbf{Y}_3\,\mathbf{E}_c}{\mathbf{Y}_1 + \mathbf{Y}_2 + \mathbf{Y}_3 + \mathbf{Y}_5}$$

---

*Complex quantities will be designated in this paper by a bold face roman type. The conjugate will be designated by old English type. Italic type indicates absolute value.

$$I_b = (Y_2 + Y_4)\,E_b - Y_2\,\frac{Y_1\,E_a + Y_2\,E_b + Y_3\,E_c}{Y_1 + Y_2 + Y_3 + Y_5}$$

$$I_c = (Y_3 + Y_6)\,E_c - Y_3\,\frac{Y_1\,E_a + Y_2\,E_b + Y_3\,E_c}{Y_1 + Y_2 + Y_3 + Y_5}$$

In this particular case, equating like coefficients:

$$Y_{aa} = Y_1\,\frac{Y_1^2}{Y_1 + Y_2 + Y_3 + Y_5}$$

$$Y_{ab} = \frac{Y_1\,Y_2}{Y_1 + Y_2 + Y_3 + Y_5}$$

$$Y_{ac} = \frac{Y_3\,Y_1}{Y_1 + Y_2 + Y_3 + Y_5}$$

$$Y_{bb} = Y_2 + Y_4 - \frac{Y_2^2}{Y_1 + Y_2 + Y_3 + Y_5}$$

$$Y_{cc} = Y_3 + Y_6 - \frac{Y_3^2}{Y_1 + Y_2 + Y_3 + Y_5}$$

$$Y_{bc} = \frac{Y_3\,Y_2}{Y_1 + Y_2 + Y_3 + Y_5}$$

In the above example, only ordinary impedances were used. The general method, however, is not limited by such restrictions, but can be applied to the representation of lines with distributed constants combined in the most complicated manner. Using the method of General Circuit Constants* developed by Messrs. Evans and Sels, the current at the sending and receiving ends of every branch in the network can always be expressed, respectively, as

$$\left.\begin{aligned} I_s &= \frac{D}{B}\,E_s - \frac{1}{B}\,E_r \\[2ex] I_r &= \frac{E_s}{B} - \frac{A}{B}\,E_r \end{aligned}\right\} \qquad (3)$$

Summing the currents at a junction point and equating to zero, an expression for the voltage at the junction point can be obtained in terms of the voltage at the adjacent junction points. Following this procedure and eliminating the voltages at all the junction points, equations can be derived expressing the currents at terminals in terms of the terminal voltages. Care must be exercised to prevent an error in sign as the method of self and mutual admittances just described assumes the current as positive when flowing *into* the network at *every terminal,* whereas the method of General Circuit Constants assumes current as positive when flowing *into* the network at supply and *out of* the network at the receiving end.

### DISCUSSION OF THE ASSUMPTIONS INVOLVED

The general method described in the previous section is the only one available for analytical calculation of stability limits of power system networks. Transformers, reactors, and lines may be represented in the usual manner by general networks with constant impedance and admittance branches. The accuracy of the general method depends upon the justification of the following approximations:

1. Synchronous machines may be represented by a source of voltage and a series impedance.
2. Loads may be represented by shunt admittances alone or in combination with synchronous machines.

The above items will be considered individually.

### REPRESENTATION OF SYNCHRONOUS MACHINES

The representation of a synchronous machine by a source of synchronous e. m. f. and a series impedance is a commonly recognized device. The value of the impedance and voltage, however, differ for various applications. For example, in short circuit calculations, the initial symmetrical value of the short circuit current is estimated on the basis that the synchronous machine is represented by a voltage corresponding to the air-gap flux and an impedance called "transient impedance"; while the sustained value of short circuit current is estimated on the basis that the synchronous machine is represented by a voltage corresponding to the excitation and an impedance called the "synchronous impedance." In stability calculations it is necessary to know not only the magnitude of machine voltage and machine impedance but also the angular relation between the terminal voltage and position of the rotor.

The machine voltage to be employed in static stability calculations depends upon whether the excitation is constant or changes importantly. For the purpose of this paper the excitation will be assumed constant, the value of the excitation being so chosen as to regulate the terminal voltage at any desired value. Mention should be made of the fact that when an automatic voltage regulator and an exciter having an extremely quick response are employed, the excitation can be increased at a rate that is sufficiently rapid to increase the static limits materially. This possibility was first recognized by Mr. E. B. Shand* and subsequently proved by calculations and experiments by the authors in 1925†. Experimental verification has also been secured by Messrs. Doherty and Nickle‡. Determination of whether a given system under control of voltage regulators is stable can be obtained by the application of the step-by-step method of transient analysis§. This discussion of the static limits with regulators has been given at some length because the methods described in the paper for the determination of static limits without regulators may be employed to give approximate limits with regulators by the use of a voltage and an impedance intermediate between the synchronous impedance and excitation voltage on the one hand and the air gap voltage and leakage or transient impedance on the other hand, the faster the response of the excitation system the closer it approaches the latter value.

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* Bibliography, Item 2.

*Bibliography, Item 5.

†Bibliography, Items 12 and 13.

‡Bibliography, Item 16.

§Bibliography, Item 12.

The impedance to be employed to represent a synchronous machine with a definite excitation is not a constant quantity and is affected by saturation. Where salient pole machines are employed another effect must be considered, namely, the saliency effect arising from non-uniform air-gap reluctance. As a consequence the machine impedance varies in magnitude and also in phase angle as a function of the real and reactive power delivered.

The synchronous machine is best analyzed by the two-reaction method due to Blondel. This method as applied to a synchronous generator is shown graphically in Fig. 5. Because of the relative unimportance of armature resistance in stability calculations this factor has been neglected. The figure is self explanatory in indicating the fundamental relations used by Blondel in his classic treatment. The effective machine impedance may be defined as that value which multiplied by $I$ vectorially will produce the voltage drop **Z$_e$ I.** This impedance may be obtained as follows:

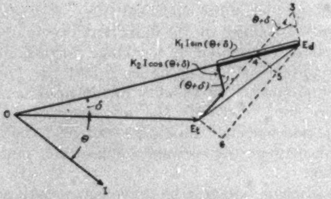

FIG. 5—VECTOR DIAGRAM FOR SYNCHRONOUS GENERATOR

$E_t$ = Terminal voltage
$I$ = Armature current
$X_1$ = Leakage reactance
$K_1$ = Reactance equivalent of armature reaction along the main axis
$K_2$ = Reactance equivalent of armature reaction along the cross axis
$E_d$ = Excitation voltage
$\theta$ = Angle between $E_t$ and $I$
= Angle between $E_d$ and $E_t$

Distance

$$
\begin{aligned}
1-3 &= K_1 I \\
1-4 &= K_2 I \\
3-4 &= (K_1 - K_2)\, I \\
4-E_d &= (K_1 - K_2)\, I \sin(\theta+\delta) \\
E_t - 6 &= 4-5 \\
&= (K_1 - K_2)\, I \sin(\theta+\delta)\cos(\theta+\delta) \\
&= \frac{(K_1 - K_2)}{2}\, I \sin 2(\theta+\delta) \\
6-5 &= (X_L + K_2)\, I \\
5-E_d &= (K_1 - K_2)\, I \sin^2(\theta+\delta) \\
&= \frac{(K_1 - K_2)}{2}\, I\,[\,1-\cos 2(\theta+\delta)\,]
\end{aligned}
$$

The effective machine impedance* may now be written as:

$$
\begin{aligned}
\mathbf{Z}_e &= \frac{1}{I}\Big[\,(E_t-6) + j\,(6-5) + j\,(5-E_d)\,\Big] \\
&= \frac{K_1-K_2}{2}\sin 2(\theta+\delta) + j\,(X_L + K_2) \\
&\quad + j\,\frac{(K_1-K_2)}{2}\,[1-\cos 2(\theta+\delta)] \\
&= j\left[X_L + \frac{K_1+K_2}{2}\right] + \left(\frac{K_1-K_2}{2}\right)\Big[\sin 2(\theta+\delta) \\
&\qquad - j\cos 2(\theta+\delta)\Big] \qquad (4)
\end{aligned}
$$

The above relation may be expressed in different notation for reactances as follows:†

$X_d = X_L + K_1$, synchronous reactance, direct axis

$X_q = X_L + K_2$, synchronous reactance, cross axis

so that the impedance becomes:

$$
\mathbf{Z}_e = +j\left(\frac{X_d+X_q}{2}\right) + \left(\frac{X_d-X_q}{2}\right)\Big[\sin 2(\theta+\delta) - j\cos 2(\theta+\delta)\Big] \qquad (5)
$$

Examination of equations (4) or (5) appear to make it difficult to determine the proper value of machine impedance. However, the fictitious resistance term $\frac{X_d - X_q}{2}\sin 2(\theta+\delta)$ is positive in a generator and negative in a motor. Consequently for the case of two similar machines operating at equal excitation and neglecting armature resistance, the total effective impedance is:

$$
\mathbf{Z}_e = 0 + j\,[\,(X_d + X_q) - (X_d - X_q)\cos 2(\theta+\delta)\,]
$$

In such a case the current is in phase with the terminal voltage so that $\theta = 0$. Hence

$$
\mathbf{Z}_e = 0 + j\left[\frac{(X_d+X_q)}{2} - \frac{(X_d-X_q)}{2}\cos 2\delta\right] \qquad (6)
$$

For such a system, pull-out will occur at about $\delta = 45$ deg. so that the value of synchronous reactance to be used is

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*Bibliography, Item 14.

†Bibliography, Item 15.

$$\mathbf{Z}_e = j\,\frac{X_d + X_q}{2} = j\left(X_L + \frac{K_1 + K_2}{2}\right) \qquad (7)$$

The effect of line reactance may be included by increasing the $X_L$ term by an amount equal to one-half of the line reactance. This is equivalent to considering the machine reactance as that defined by equation (**7**) even though that equation was derived for the assumption of zero line reactance. For the normal machine in which $K_2 = 0.5\,K_1$, this defines $Z_e$ as equal to $X_L + 0.75\,K_1$.

The general representation of systems by means of impedance networks as defined by equation (**1**) require that all impedances in the system be constant and independent of the current, voltage, or phase relation between currents and voltages. The impedance of machines, as defined by equation (**5**) however, is not independent of the angles between current and terminal and excitation voltages. For this reason, while this impedance is accurate for most purposes, it is not theoretically correct but is sufficiently accurate for substitution in formulas for the criterion of stability to be discussed later.

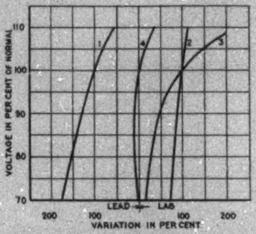

FIG. 6—VARIATION OF REACTIVE KV-A. WITH VOLTAGE

1. Synchronous motor—75 per cent load, 85 per cent power factor. lead (at normal voltage)
2. Induction motor, 75 per cent load, 79 per cent power factor lag (average at normal voltage)
3. Transformer exciting kv-a.
4. Synchronous converter (reactive kv-a. in per cent of machine rating),

The acceleration of the rotor of a synchronous machine varies directly as the difference of the torque due to the prime mover and the magnetic torque reacting on the rotor and inversely as the mechanical inertia of the rotor. In stability calculation, the actual velocity is so nearly constant that the acceleration is proportional to the difference in power input and output. A convenient formula for obtaining the acceleration is derived in Appendix III which is as follows:

$$\alpha = \frac{180\,f}{W}\,\Delta P \qquad (8)$$

## LOAD CHARACTERISTICS

The load at the receiving end of a transmission system consists of induction motors, lighting, synchronous motors, and synchronous converters with the first named predominating.

The various types of load have different characteristics. With synchronous and induction motors, the true power demand may be assumed to remain constant with variation in voltage, whereas lighting and synchronous converter load will vary as the square of the voltage. The reactive power demand varies greatly with the different types of load and the variation of reactive power with terminal voltage for typical loads are shown in the curves of Fig. 6.*

It is impractical to consider a multitude of individual loads, and it therefore becomes necessary to use some composite load characteristics such as shown in Fig. 7. These load characteristics must also take into account the effect of local supply lines and transformers impedance and admittances. Such a characteristic load curve is difficult to handle analytically so it is pertinent to consider suitable approximations such as the shunt admittance of constant value indicated by the dotted line of Fig. 7. It should be noted that the constant admittance method is optimistic so far as true power is concerned and pessimistic in regard to reactive power changes. The justification for this approximation follows from the application of an accurate method to a number of special cases. The accurate solution is of course obtained by employing the actual data as to the rates of change of real and reactive power as described in the Appendix II. Calculations were made on a simple transmission system for a variety of load conditions. The study of these results given in the Appendix indicates that shunt admittances represent not only a desirable approximation but a highly accurate one as well. Furthermore, it is possible to combine shunt admittance with the synchronous machine characteristics to obtain a combination still more nearly representative of all receiving end characteristics.

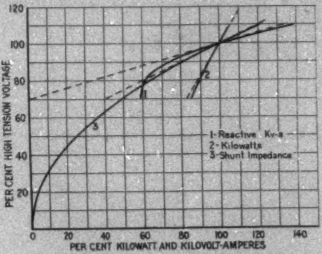

FIG. 7—TYPICAL LOAD CHARACTERISTIC CURVE

## TWO MACHINE PROBLEM

The problem involving two sources of synchronous a-c. voltages has been termed the "Two Machine

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*Bibliography, Item 12.

Problem." The solution given here represents the general case for any two synchronous machines connected to networks in which the load can be represented by pure admittances or shaft loads on the synchronous machines. These machines may be operating as two generators, as one generator and one motor, or as one generator and a condenser. The current at the terminals of the machines can always be expressed in terms of the internal voltages by the following equations:

$$\left.\begin{aligned} \mathbf{I}_a &= \mathbf{Y}_{aa}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b \\ \mathbf{I}_b &= -\,\mathbf{Y}_{ab}\,\mathbf{E}_a + \mathbf{Y}_{bb}\,\mathbf{E}_b \end{aligned}\right\} \tag{9}$$

in which currents in the positive sense are taken as flowing *out* of the machine and *into* the network, $\mathbf{I}_a$ and $\mathbf{I}_b$ are line currents and $\mathbf{E}_a$ and $\mathbf{E}_b$ are star voltages which are considered as being secured rigidly to the rotor so that their time rates of change are determined by the time rates of change of their rotors.

The real and reactive components of power output of the two generators are:

$$\begin{aligned} P_a + j\,Q_a &= 3\,\mathbf{E}_a\,\mathfrak{I}_a \\ &= 3\,\mathfrak{Y}_{aa}\,E_a^2 - \mathfrak{E}\,\mathfrak{Y}_{ab}\,\mathbf{E}_a\,\mathfrak{E}_b \\ P_b + j\,Q_b &= 3\,\mathbf{E}_b\,\mathfrak{I}_b \\ &= -\,3\,\mathfrak{Y}_{ab}\,\mathfrak{E}_a\,\mathbf{E}_b + 3\,\mathfrak{Y}_{bb}\,E_b^2 \end{aligned}$$

or in terms of their line to line voltages:

$$\left.\begin{aligned} P_a + j\,Q_a &= \mathfrak{Y}_{aa}\,E_A^2 - \mathfrak{Y}_{ab}\,\mathbf{E}_A\,\mathfrak{E}_B \\ P_b + j\,Q_b &= -\,\mathfrak{Y}_{ab}\,\mathfrak{E}_A\,\mathbf{E}_B + \mathfrak{Y}_{bb}\,E_B^2 \end{aligned}\right\} \tag{10}$$

Let

$$\left.\begin{aligned} \mathbf{E}_A &= E_A\,\epsilon^{j\phi_A} \\ \mathbf{E}_B &= E_B\,\epsilon^{j\phi_B} \\ \mathbf{Y}_{ab} &= Y_{ab}\,\epsilon^{j\phi_1} \\ \mathbf{Y}_{aa} &= Y_{aa}\,\epsilon^{j\phi_7} \\ \mathbf{Y}_{bb} &= Y_{bb}\,\epsilon^{j\phi_8} \end{aligned}\right\} \tag{11}$$

then

$$\left.\begin{aligned} P_a + j\,Q_a &= Y_{aa}\,E_A^2\,\epsilon^{-j\phi_7} \\ &\qquad - Y_{ab}\,E_A\,E_B\,\epsilon^{j(\phi_A - \phi_B - \phi_1)} \\ P_b + j\,Q_b &= -\,Y_{ab}\,E_A\,E_B\,\epsilon^{j(\phi_B - \phi_A - \phi_1)} \\ &\qquad + Y_{bb}\,E_B^2\,\epsilon^{-j\phi_8} \end{aligned}\right\} \tag{12}$$

and since $\epsilon^{j\theta} = \cos\theta + j\sin\theta$

$$\left.\begin{aligned} P_a &= Y_{aa}\,E_A^2\cos\phi_7 \\ &\qquad - Y_{ab}\,E_A\,E_B\cos(\phi_A - \phi_B - \phi_1) \\ P_b &= -\,Y_{ab}\,E_A\,E_B\cos(\phi_A - \phi_B + \phi_1) \\ &\qquad + Y_{bb}\,E_B^2\cos\phi_8 \end{aligned}\right\} \tag{13}$$

These equations define the electrical output at *a* and at *b*. The mechanical input will be designated by $P_{ga}$ and $P_{gb}$ in which input as for a generator will be considered positive and input as for a motor having a shaft load as negative. The difference between the input and output of say a turbine-generator set is thus expressed by $P_{ga} - P_a$. This can be converted to acceleration of the rotor by means of equation (8), so that $\alpha_A$ or $\dfrac{d^2\phi_A}{d\,t^2}$, is equal to

$$\begin{aligned} \alpha_A = \frac{d^2\phi_A}{d\,t^2} &= \frac{180\,f}{W_a}\,(P_{ga} - P_a) \\ &= \frac{180\,f}{W_a}\,P_{ga} - \frac{180\,f}{W_a}\,Y_{aa}\,E_A^2\cos\phi_7 + \\ &\quad + \frac{180\,f}{W_a}\,Y_{ab}\,E_A\,E_B\cos(\phi_A - \phi_B - \phi_1) \end{aligned} \tag{14}$$

$$\begin{aligned} \alpha_B = \frac{d^2\phi_B}{d\,t^2} &= \frac{180\,f}{W_b}\,(P_{gb} - P_b) \\ &= \frac{180\,f}{W_b}\,P_{gb} - \frac{180\,f}{W_b}\,Y_{bb}\,E_B^2\cos\phi_8 \\ &\quad + \frac{180\,f}{W_b}\,Y_{ab}\,E_A\,E_B\cos(\phi_A - \phi_B + \phi_1) \end{aligned} \tag{15}$$

These expressions determine the rate of change in the absolute position of the voltage vectors. In the final analysis, however, it is the variation of the difference in angle between the two voltages, the phase angle difference, that is really important. So long as the phase difference between the two voltages does not exceed a certain value the actual changes in their position in space is unimportant.

Let

$$\phi_A - \phi_B = \phi \tag{16}$$

$$\frac{d^2\phi}{d\,t^2} = \frac{d^2\phi_A}{d\,t^2} - \frac{d^2\phi_B}{d\,t^2} = \alpha_A - \alpha_B = \alpha \tag{17}$$

From equations (14) and (15)

$$\begin{aligned} \alpha = 180\,f \Bigg\{ & \frac{P_{ga}}{W_a} - \frac{P_{gb}}{W_b} + \frac{Y_{bb}\,E_B^2}{W_b}\cos\phi_8 \\ & - \frac{Y_{aa}\,E_A^2}{W_a}\cos\phi_1 + Y_{ab}\,E_A\,E_B \\ & \left[ -\left(\frac{1}{W_a} - \frac{1}{W_b}\right)\cos\phi_1\cos\phi \right. \\ & \left. + \left(\frac{1}{W_a} + \frac{1}{W_b}\right)\sin\phi_1\sin\phi \right] \Bigg\} \end{aligned} \tag{18}$$

This equation completely determines the oscillation between the machines resulting from a disturbance for the given circuit conditions, voltages, inertias, and governor settings. Circuit conditions, inertia of machines, shaft loads of motors, and prime mover inputs of generators can be assumed constant, the last named because of the relatively sluggish action of governors. The voltages appearing in the equations are machine voltages which are assumed constant in magnitude.

The above equation can be solved by elliptic functions or by step-by-step methods. For small variations from the mean angle the following method may be used.

$$\Delta \alpha = \frac{d\,\alpha}{d\,\phi}\,\Delta\,\phi$$

$$= 180\,f\,Y_{ab}\,E_a\,E_b\Big[-\Big(\frac{1}{W_a}-\frac{1}{W_b}\Big)\cos\phi_1\sin\phi\,+$$

$$+\Big(\frac{1}{W_a}+\frac{1}{W_b}\Big)\sin\phi_1\cos\phi\Big]\,\Delta\,\phi \qquad \textbf{(19)}$$

It is interesting to note that only the mutual admittance enters this equation, the two self impedances disappearing because they are not associated with terms that vary with the angle.

In analyzing the conditions for stable operation at a given operating point several criteria suggest themselves. One of the rotors can be displaced forcibly from its position of equilibrium and the relations analyzed to determine whether it will return to its original position. An increment of load could be placed on the shaft of one unit and the conditions investigated for stable operation. Another disturbance suggests itself in decreasing the network load by changing the network constants. The latter two involve a change in frequency or governor setting to determine the final steady state operating conditions. For this reason the change in angular position constituting the disturbing factor will be selected.

The criterion for stability shall be that the system return to its original position after a slight displacement of the angle between the machines. Let $\phi_0$ be the steady state angle and $\theta$ the departure of $\phi$ from this angle, then

$$\phi = \phi_0 + \theta \qquad \textbf{(20)}$$

$\Delta\,\phi$ is then equal to $\theta$ for small value of $\theta$ and $\alpha = \frac{d^2\,\phi}{d\,t^2} = \frac{d^2\,\theta}{d\,t^2}$. Since the acceleration is zero for $\phi = \phi_0$, everything being balanced for this particular value, then $\Delta\,\alpha = \alpha$ for small values of $\alpha$.

Equation (**19**) may now be written

$$\frac{d^2\,\theta}{dt^2} = 180\,f\,Y_{ab}\,E_a\,E_b\Big[-\Big(\frac{1}{W_a}-\frac{1}{W_b}\Big)\cos\phi_1\sin\phi_0$$

$$\Big(\frac{1}{W_a}+\frac{1}{W_b}\Big)\sin\phi_1\cos\phi_0\Big]\cdot\theta \qquad \textbf{(21)}$$

This has the same form as the simple differential equation

$$\frac{d^2\,\theta}{dt^2} = K\,\theta \qquad \textbf{(22)}$$

which is the equation for simple harmonic motion so long as $K$ is negative. The condition then that the motion resulting from a disturbance be oscillatory and not continue with increasing angle and finally pull out is that the coefficient of $\theta$ be negative; then for any small displacement $\theta$ the rotors will always return to their original relative position. Since the quantity $180\,f\,Y_{ab}\,E_a\,E_b$ is positive the condition for stable operation reduces to the relation that

$$\Big(\frac{1}{W_a}+\frac{1}{W_b}\Big)\sin\phi_1\cos\phi_0$$

$$-\Big(\frac{1}{W_a}-\frac{1}{W_b}\Big)\cos\phi_1\sin\phi_0 < 0 \qquad \textbf{(23)}$$

The limiting condition is reached for that value of $\phi_0$ for which

$$\Big(\frac{1}{W_a}+\frac{1}{W_b}\Big)\sin\phi_1\cos\phi_0$$

$$-\Big(\frac{1}{W_a}-\frac{1}{W_b}\Big)\cos\phi_1\sin\phi_0 = 0$$

or for

$$\tan\phi_0 = \frac{W_b + W_a}{W_b - W_a}\tan\phi_1 \qquad \textbf{(24)}$$

It can be seen from this that the limiting angle is a function of the inertia of the two machines and of the argument of the complex number representing the mutual admittance $Y_{ab}$. This result is contrary to the previously accepted theory which neglected the influence of the relative values of the inertia.

For

$$W_a = \infty$$

$$\tan\phi_0 = -\tan\phi_1$$

$$\phi_0 = -\phi_1 + n\,\pi$$

where $n$ is any integral number.

For $W_b = \infty$

$$\phi_0 = \phi_1 + m\,\pi$$

For $W_a = W_b$

$$\phi_0 = \pi/2 \qquad \textbf{(25)}$$

For those cases usually met in practise in which $a$ is the sending end and $b$ the receiving end of a transmission system

$n = 0$ and $m = 1$, so that

for

$$W_a = \infty,\ \phi_0 = -\phi_1 \qquad \textbf{(26)}$$

and for

$$W_b = \infty,\ \phi_0 = \pi + \phi_1 \qquad \textbf{(27)}$$

These general considerations, perhaps, may be seen more clearly by analyzing the expressions for $\alpha_a$ and $\alpha_b$ in the light of the power circle diagrams. Consider machine $a$ as a generator and machine $b$ as a motor connected by a simple impedance $\mathbf{Z}$. The motor shall be loaded by a shaft load of essentially constant power. (see Fig. 8) The coefficients for this case will then be:

$$\mathbf{Y}_{aa} = \mathbf{Y}_{ab} = \mathbf{Y}_{bb} = \frac{1}{R + j\,X} = \frac{1}{Z\,\epsilon^{j\psi}} = \frac{1}{Z}\,\epsilon^{-j\psi}$$

so that equations (**12**) become

$$P_a + j\,Q_a = \frac{1}{Z}\,E_A{}^2\,\epsilon^{j\psi} - \frac{1}{Z}\,E_A\,E_B\,\epsilon^{j(\phi+\psi)} \qquad (\mathbf{28})$$

$$P_b + j\,Q_b = -\frac{1}{Z}\,E_A\,E_B\,\epsilon^{j(-\phi+\psi)} + \frac{1}{Z}\,E_B{}^2\,\epsilon^{j\psi} \qquad (\mathbf{29})$$

Reversing the positive reference of current flow at *B* to correspond to the more usual practise the power expression for *B* becomes:

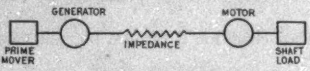

FIG. 8—SIMPLE POWER SYSTEM

$$P_{b1} + j\,Q_{b1} = +\frac{1}{Z}\,E_A\,E_B\,\epsilon^{j(-\phi+\psi)} - \frac{1}{Z}\,E_B{}^2\,\epsilon^{j\psi} \qquad (\mathbf{30})$$

Equations (**28**) and (**29**) can be plotted in the usual form of power circle diagrams shown in Fig. 9. The point *a*, being the center of the sending-end circle, is determined by the first term in equation (**28**); the second term may be drawn with *a* as center and radius equal to the absolute value of the second term. For $\phi = 0$ the line will lie along *o a*. This line constitutes the reference line. For other values of $\phi$ the particular angle is measured from this line, positive angles rotating the vector counter-clockwise. The receiver circle is plotted in a similar manner with center at *b* determined by the last term of equation (**30**). Positive angles are measured in clockwise rotation from *b o*. Now suppose the systems were operating at the point *c* on the sending end circle which corresponds to *d* on the receiving circle. The governor would be set for the power corresponding to *c* and the power, or torque since speed changes so slightly, on the motor would correspond to point *d*. Any slight instantaneous change in the operating angle would change the operating points to *c′* and *d′*. Since the governor setting and motor torque are constant the increased power output at the generator end tends to slow up the rotor of the generator and speed up the rotor of the motor and thus reestablish the original operating angle. This is an inherently stable operating position. The acceleration at either end varies directly as the excess of output over input and inversely as the inertia of the rotor. The actual rate of change, the resultant acceleration, of the angle is a resultant of the effects at the two ends. Both effects act in the same direction up to the angle corresponding to maximum power at the receiver (point of vertical tangency), *i. e.,* up to this point a small increment in angle produces retardation of the rotor at the generator or sending end and *acceleration* of the rotor of the motor but both effects tend to *decrease* the angle and to this extent act in the same direction. Slightly beyond this point an increment in angle produces retardation of the rotor at the receiving end. Both ends are now retardation. The resultant effect on the system depends upon which of the two retardations is the greater and these in turn are dependent upon the relative inertias of the two machines. For equal inertias and angles less than $\pi/2$, the generator will retard faster than the motor for positive increments in angle. When the angle is $\pi/2$ the retardation are equal but within the range of line angle, $\psi$ to $\pi/2$, while both ends retard the generator retards sufficiently rapidly to maintain synchronism. The system as a whole will retard, reducing the frequency, but this will be taken care of by the automatic governors.

When the inertia of the generator is infinite the acceleration of the generator for any finite change in power is zero, so that the acceleration or retardation of the angle is determined entirely by that of the motor rotor. For positive increments in angle the acceleration of the motor rotor is positive up to the point where the line angle reaches $\psi$, beyond which it becomes negative. The stability of the system for this condition is coincident with the condition of maximum power at the receiver (*d″* in Fig. 9) and the line angle is $\psi$, the argument of the complex number representing the admittance $\mathbf{Y}_{ab}$. When the inertia of the motor rotor is infinite the limit is determined for similar reasons by the condition of maximum power at the generator. This corresponds to a line angle of $\pi - \psi$, the operating points of which are indicated by *c‴* and *d‴* in Fig. 9. It is interesting to note in this connection that it is not only possible theoretically to operate beyond the point of maximum power of the receiving circle diagram such

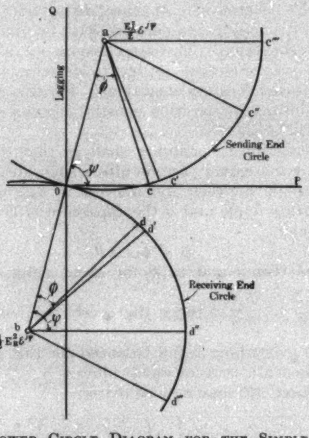

FIG. 9—POWER CIRCLE DIAGRAM FOR THE SIMPLE POWER SYSTEM SHOWN IN FIG. 8

as discussed for conditions when the inertia of the rotor of generator is other than infinite, but it is possible to operate beyond an angle of $\pi/2$, when the inertia at the receiving end is greater than that at the generator. While this is the condition usually met in practise it is not being advocated here to operate a system within that zone.

It follows from the above discussion that while the point of maximum power might be a stable operating point this method might give a result which would indicate that for the maximum angle at which it is possible to operate, the stability limit is lower than the maximum power, (*i. e.*, that the power at say $d'''$ is lower than at $d''$). But to arrive at this operating point it is necessary with slowly increasing load to pass through the point of maximum power of the circle diagram. In such case the system reaches a maximum power limit before a stability limit. These ideas are merely being developed here to insure a clearer conception of static stability. Some of these operating conditions which are here shown to be stable were heretofore considered inherently unstable.

The natural period of a system varies with the magnitude of the oscillation and with the load. For small variations of angle the differential equation takes the form of equation (**22**). The natural period obtained from a solution of this equation is

$$T = \frac{2\,\pi}{\sqrt{-K}}$$

for $K$ negative. The constant $K$ is the slope of the acceleration curve plotted as a function of the angle and is equal to $\frac{\alpha}{\theta}$

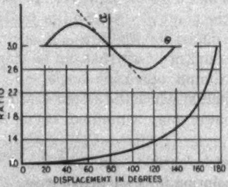

FIG. 10—CURVE SHOWING RATIO BETWEEN NATURAL PERIOD FOR SINUSOIDAL VARIATION OF $\alpha$ AND LINEAR VARIATION OF $\alpha$ PLOTTED AS A FUNCTION OF DISPLACEMENT

therefore

$$T = 2\,\pi\,\sqrt{\frac{\theta}{\alpha}} \tag{31}$$

and is expressed in seconds when $\theta$ is expressed in electrical degrees and $\alpha$ in electrical degrees per second per second. As can be seen from equation (**21**). $\frac{\theta}{\alpha}$ increases with increasing angle, so that the natural period increases with angle or with load, reaching an infinitely large value at the static limit. Of course, all these considerations imply constant internal voltage. The increased natural period near the limit permits more time for the operation of automatic voltage regulators and exciters and indicates that the period near the limit is determined more by magnetic phenomena in the machines than by electromechanical phenomena.

In general, increasing the amplitude of the oscillation increases the natural period. For small oscillations the curve of $\alpha$ against $\theta$ can be considered linear, but for larger oscillations this is not justified. The correction, however, for amplitudes ordinarily met in practise is not great. For example, if the acceleration is a sinusoidal function of the angle the ratio of the actual period to that obtained by taking the slope for $\theta = 0$ is shown in Fig. 10.

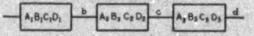

FIG. 11—GENERAL CASE OF TWO MACHINES WITH VOLTAGE MAINTAINED AT $b$ AND $c$

## PRACTICAL CALCULATION OF STATIC STABILITY

In general, the voltage will be maintained constant at various points in the system and as the load varies the excitation must be changed either manually or by means of automatic voltage regulators to maintain this voltage. Because of this changing excitation and internal voltage it would be necessary by the method just described to calculate the angle and the internal voltage for each condition and then apply the criterion for stability to determine whether the system is stable or not. The following method for the calculation of maximum power does not require the knowledge of the internal voltage.

The most general case in which the problem can still be reduced to a single synchronous machine at each end is that shown in Fig. 11 in which the three rectangles represent general networks, $\mathbf{E}_a$ and $\mathbf{E}_d$ the internal voltages (to neutral) and $b$ and $c$ the points at which the voltages are maintained. The three general networks in series can be combined into one equivalent so that the following expression is obtained:

$$\mathbf{E}_a = \mathbf{A}_0\,\mathbf{E}_d + \mathbf{B}_0\,\mathbf{I}_d \tag{32}$$

where, $\mathbf{A}_0$ and $\mathbf{B}_0$ are the general circuit constants for the three combined networks, $\mathbf{E}_a$ and $\mathbf{E}_d$ the star voltages at $a$ and $d$ respectively and $\mathbf{I}_d$ the current at $d$.

Transposing equation (**32**)

$$\mathbf{I}_d = \frac{1}{\mathbf{B}_0}\,\mathbf{E}_a - \frac{\mathbf{A}_0}{\mathbf{B}_0}\,\mathbf{E}_d \tag{33}$$

from which it is seen that

$$\mathbf{Y}_{ab} = Y_{ab}\,\epsilon^{j\phi_1} = \frac{1}{\mathbf{B}_0} \tag{34}$$

But

$$\mathbf{B}_0 = \mathbf{A}_1 (\mathbf{B}_3 \mathbf{A}_2 + \mathbf{D}_3 \mathbf{B}_2) + \mathbf{B}_1 (\mathbf{B}_3 \mathbf{C}_2 + \mathbf{D}_3 \mathbf{D}_2) \quad (35)$$

so that $\phi_1$ is the negative of the argument of the complex number $\mathbf{B}_0$. The limiting angle, $\phi_0$, is related to $\phi_1$ by the relation expressed by equation (**24**) and is dependent upon the relative inertias.

Having obtained the maximum overall angle corresponding to the limit of stability, the actual value of power delivered can be determined by the following graphical means. From a knowledge of $\mathbf{A}_2$, $\mathbf{B}_2$, $\mathbf{C}_2$, $\mathbf{D}_2$ and the voltages at *b* and *c*, the sending and receiving-end power circle diagrams for the middle section can be drawn as shown by the heavy lines in Fig. 12. For any angle $\beta$ between the voltages at *b* and *c* the power flow at these points is indicated by the points *m* and *n*. Every point such as *m* on the supply circle must also represent a point on the receiving circle for the first section. This latter circle is represented by the expression

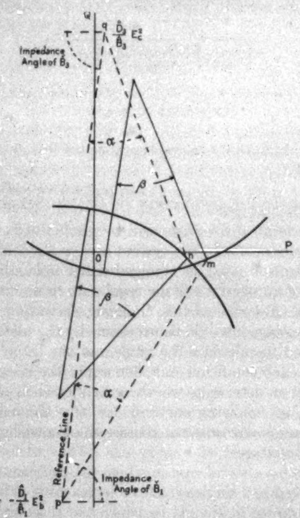
Q
T
q
$\frac{\hat{D}_3}{\hat{B}_3} E_c^2$
Impedance Angle of $\hat{B}_3$
α
β
O
P
n
m
β
α
Reference Line
Impedance Angle of $\check{B}_1$
$-\frac{\hat{D}_1}{\hat{B}_1} E_b^2$
p

FIG. 12—POWER CIRCLE DIAGRAMS FOR TWO-MACHINE PROBLEMS

$$P_b + j\,Q_b = \frac{1}{\mathfrak{B}_1} E_A\, E_B\, \epsilon^{-j\alpha} - \frac{\mathfrak{A}_1}{\mathfrak{B}_1} E_B{}^2$$

The center of this circle is located at $-\dfrac{\mathfrak{A}_1}{\mathfrak{B}_1} E_B{}^2$.

It will be noted that all of these quantities are known and can be plotted as shown by the point *p*. Now while the value of the voltage $\mathbf{E}_A$ is unknown (and incidentally will not be necessary to determine) the reference vector from which the angle $\alpha$ is measured can be drawn making an angle with the horizontal equal to that of $\dfrac{1}{\mathfrak{B}_1}$ which angle is the same as the angle of $\mathbf{B}_1$, *i. e.*, $\tan^{-1} \dfrac{b_1}{a_1}$ where $\mathbf{B}_1 = a_1 + j\,b_1$. As stated previously, the point *m* must lie on the receiving power circle diagram for the first section, and therefore, the angle $\alpha$ between *p m* and the reference line indicates the angle between the voltages at *a* and *b* for the power transmitted at *c* corresponding to point *n*.

A similar construction applies to the receiving-end network. The power at *c* into this network is expressed

$$P_c + j\,Q_c = \frac{\mathfrak{D}_3}{\mathfrak{B}_3} E_C{}^2 - \frac{1}{\mathfrak{B}_3} E_C\, E_D\, \epsilon^{+j\gamma}$$

The center of the circle *q* is determined by $\dfrac{\mathfrak{D}_3}{\mathfrak{B}_3} E_C{}^2$ and the reference line makes an angle with the horizontal equal to that of $-\dfrac{1}{\mathfrak{B}_3}$, *i. e.*, $\tan^{-1} \dfrac{b_3}{a_3}$ where $\mathfrak{B}_3 = a_3 + j\,b_3$.

The angle $\gamma$ between *n q* and the reference line indicates the angle between the voltages at *c* and *d*. Therefore, $\alpha + \beta + \gamma$ gives the total angle between the voltages at *a* and *d* for the power conditions at *c* corresponding to the point *n*. After a few trials the point *n* can be determined for which $\alpha + \beta + \gamma = \phi_0$. This gives the amount of power that can be transmitted at *c* for the maximum operating angle $\phi_0$. This is the maximum angle at which the system is still stable. The maximum power may sometimes occur for a smaller angle.

The general method can best be illustrated by means of a solution for a particular case. The example chosen is the determination of the static power limit for a 270,000-kv-a. generator, transformers, a 250-mile line and a 170,000-kv-a. synchronous motor. The voltage at the generator and motor terminals will be maintained at an equivalent of 220 kv. by hand regulation. The constants of the line and machines are as follows:

Line Constants:

| | |
|---|---|
| Length of line | = 250 miles |
| Frequency | = 60 cycles |
| Resistance per mile | = 0.151 ohms |
| Reactance per mile | = 0.813 ohms |
| Admittance per mile | = 5.22 micro-mhos |
| Conductance per mile | = 0 |

Step-up Transformers:

270,000 kv-a. total. 12% Reactance
13,200—220,000 volts.

Step-down Transformers:

240,000 kv-a. total. 12% Reactance
210,000—13,200 volts

Generators:

270,000 kv-a. total
0.9 power-factor, 13,200 volts
100% Synchronous impedance.

Synchronous Motor:

170,000 kv-a.
85% Synchronous impedance.

The combined constants for transformers and line are:

$$\mathbf{A}_2 = 0.8431 + j\,0.0279$$
$$\mathbf{B}_2 = 39.6 + j\,232.1$$
$$\mathbf{C}_2 = (0.0104 + j\,1.248)\,10^{-3}$$
$$\mathbf{D}_2 = 0.8428 + j\,0.0280$$

These constants are sufficient to permit the construction of the sending and receiving power circle diagrams in the ordinary way. These are indicated by the full lines in Fig. 13.

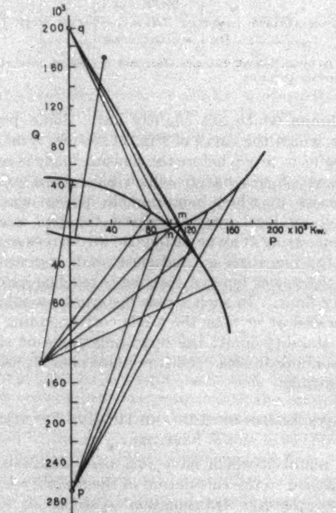

Fig. 13—Circle Diagram for Illustration of Two-Machine Problem

The center of the receiving circles for network 1 is located at $-\dfrac{\mathfrak{A}_1}{\mathfrak{B}_1}E_B^2$. Since this network contains only the generator reactance

$$\mathbf{A}_1 = 1.0 + j\,0$$
$$\mathbf{B}_1 = 0 + j\,X_1$$

and

$$\frac{\mathfrak{A}_1}{\mathfrak{B}_1} = \frac{1}{-j\,X_1}$$

$$-\frac{\mathfrak{A}_1}{\mathfrak{B}_1}E_B^2 = -j\,\frac{E_B^2}{X_1}$$

$$= -j\,\frac{220 \times 220{,}000}{179.2} = -j\,270{,}000 \text{ kv-a.}$$

Incidentally, this is equal to the sustained short circuit kv-a. at the point $b$. The center of the generator circle is indicated by the letter $p$ on Fig. 13. The reference line coincides with the axis of reactive power.

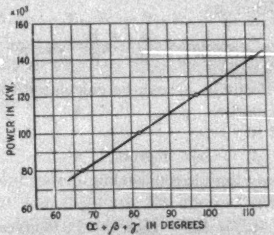

Fig. 14—Power-Angle Diagram for System of Figs. 11 and 13

The center of the sending circles for network 3 is obtained in a similar manner.

$$\mathbf{D}_3 = 1.0$$
$$\mathbf{B}_3 = 0 + j\,X_3$$
$$\frac{\mathfrak{D}_3}{\mathfrak{B}_3} = \frac{1}{-j\,X_3}$$

The center is located at

$$\frac{\mathfrak{D}_3}{\mathfrak{B}_3}E_C^2 = \frac{E_C^2}{-j\,X_3}$$

$$= j\,\frac{200 \times 200{,}000}{200} = j\,200{,}000$$

This point is plotted at $q$, the reference line being the axis of reactive power.

Now give $\beta$ an arbitrary value, say 34 degrees, and determine $m$ and $n$ for this value. Draw $m\,p$ and $n\,q$ and measure $\alpha$ and $\gamma$.

$$\alpha = 22.3 \text{ degrees}$$
$$\gamma = 26.0 \text{ degrees}$$
$$\alpha + \beta + \gamma = 82.3 \text{ degrees}$$

The total angle between internal voltages is then equal to 82.3 degrees for 100,000 kw. transmitted at the receiving end. Choose a different value of $\beta$ and repeat. By this means the curve in Fig. 14 can be obtained.

The final step consists in determining the limiting angle. If the inertias of the two machines are equal the limiting angle is 90 deg. and the power corresponding to this angle can be read directly from the curve and is found to be 111,000 kw. When $W_a \neq W_b$ it is necessary to calculate $\phi_0$ from equation (**24**). Substituting in equation (**35**) $\mathbf{B}_0$ is found equal to

$$\mathbf{B}_0 = 28.6 + j\,506.7$$

and

$$\phi_1 = -\tan^{-1}\frac{506.7}{28.6} = -86.7 \text{ degrees.}$$

From equation (**24**)

$$\phi_0 = \tan^{-1}\frac{W_b + W_a}{W_b - W_a}\tan\phi_1$$

Using this formula $\phi_0$, can be calculated for any combination of inertias.

If $W_a = \infty$

$\phi_0 = 86.7$ degrees.

and the power limit is 106,500 kw.

If $W_b = \infty$

$\phi_0 = 180 - 86.7 = 93.3$ degrees.

and the power limit is 116,000 kw.

For other values of inertia, the power limit will be somewhere between these two limits. For example, if the stored energy at the receiving end is twice that at the sending end

$$\phi_0 = -\tan^{-1}\frac{3}{1}\cdot\frac{506.7}{28.6} = 92.2 \text{ degrees.}$$

and the power limit is 113,000 kw.

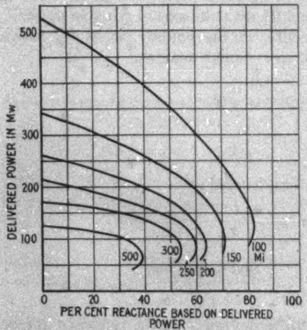

FIG. 15—STABILITY LIMIT OF 220-KV. SYSTEMS HAVING IDENTICAL GENERATORS AND MOTORS

3-phase, 60-cycle, 795,000-cir. mils aluminum condenser, steel reinforced 29-ft. equivalent spacing

For those problems involving low inertia hydroelectric generating stations feeding a load through long lines the stored energy at the receiving end is usually larger than at the sending end so that the limiting angle is usually larger than 90 degrees. It is, therefore, usually found that using 90 degrees as the limiting angle gives limits which are slightly low. Some problems arise in which the curve of Fig. 14 reaches a maximum and begins to droop before the limiting angle is reached. The cases of this nature which have been examined were cases in which considerable power was being supplied by local generators and the line itself was really operating at an angle beyond 90 degrees so that as far as the line itself is concerned, with increasing line angle, the power limit of the line is reached before the stability limit. In such a case the system would never be operated at or near the angle corresponding to the actual stability limit; the operating angle of the line corresponding to this condition represents an impractical condition.

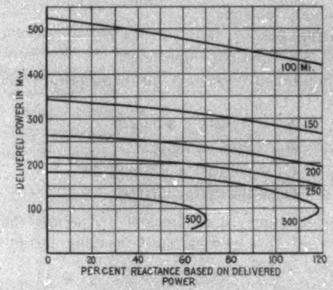

FIG. 16—STABILITY LIMIT OF 220-KV. SYSTEM WITH INFINITE BUS AT RECEIVER

3-phase, 60-cycle, 795,000-cir. mils aluminum condenser, steel reinforced, 29-ft. equivalent spacing

## STABILITY LIMITS OF 220- AND 110-KV. TRANSMISSION SYSTEMS

The methods which have just been described have been applied to the calculation of the stability limits of 60-cycle, 220-kv. transmission systems of various lengths. Fig. 15 shows the stability limits for systems with generator and step-up transformer at one end and step-down transformer and synchronous motor at the other end, the generator and motor being identical in electrical and mechanical characteristics, and the voltage being maintained at 220 kv. on the high voltage side of the transformers. Fig. 16 shows the stability limits for the same lines fed into an infinite bus at the receiving end, that is, the voltage at the receiving end is maintained constant at 220 kv. and the inertia of the apparatus at the receiving end is assumed to be infinitely large. In both cases the generator reactance in per cent was based upon the delivered power.

The curves of Figs. 15 and 16 may be used in estimating the static stability of systems by considering how the particular system approaches either of these conditions upon which the calculations were based. These curves will also be found useful in comparing the relative effects of generator reactance and length of line upon the stability limits. It should be borne in mind that these results do not indicate the value at which it is desirable to operate the system but rather that they represent the very limit of power which can be transmitted and that the system should be so designed that even during emergency conditions these values should not be approached.

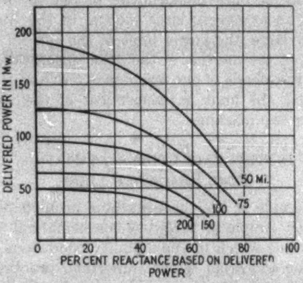

Fig. 17—Stability Limits of 110-Kv. Systems Having Identical Generators and Motors

3-phase, 60-cycle, 4-0 copper, 13-ft. equivalent spacing

Figs. 17 and 18 show similar static power limits for a typical single-circuit, 110-kv. system. The assumptions as to load were identical.

### Three-Machine Problem

A large percentage of the problems met in practise can be reduced to the equivalent of a two generator problem—a synchronous generator at the sending end and a synchronous motor or generator supplying a local load at the receiving end. There exist, however, a large number of problems which can not be so simplified. A particular case, and one with which this paper is largely concerned is that of ascertaining the effect of an intermediate condenser station in improving the stability limit. This type of problem has been termed "the three-machine problem," because, in the general case it involves three sources of synchronous e. m. fs. The solution of this problem immediately permits of the solution of a large number of problems previously considered too involved or complicated. The number that may be so solved are fewer than those that may be solved by the two-machine problem. There still remain a large number of problems which lie beyond the scope of either the two- or three-machine problem. The solution of some of these, inherently involve the addition of another source of synchronous e. m. f., requiring the solution of the "four-machine problem." A particular case of this type and one with which this paper is concerned, is that of a transmission system with two intermediate condenser stations. The solution of the three-machine problem will now be discussed.

As shown previously, the general circuit conditions for the three-machine problem in which loads are represented by impedances, are completely defined by the following equations:

$$\mathbf{I}_a = \mathbf{Y}_{aa}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b - \mathbf{Y}_{ac}\,\mathbf{E}_c$$
$$\mathbf{I}_b = -\,\mathbf{Y}_{ba}\,\mathbf{E}_a + \mathbf{Y}_{bb}\,\mathbf{E}_b - \mathbf{Y}_{bc}\,\mathbf{E}_c$$
$$\mathbf{I}_c = -\,\mathbf{Y}_{ca}\,\mathbf{E}_a - \mathbf{Y}_{cb}\,\mathbf{E}_b + \mathbf{Y}_{cc}\,\mathbf{E}_c$$

As shown in Appendix I, the conditions which must be fulfilled at all times so that the system remains in synchronism are,

$$\left.\begin{array}{l} a > 0 \\ b > 0 \\ a^2 > 4\,b \end{array}\right\} \qquad (36)$$

in which $a$ and $b$ are functions of the network constants, the inertia of the machines, the internal voltages, and the angles between the internal voltages. These functions are derived in the appendix.

The above relations supply a test which can always be applied for the stability of a three-machine system. This type of problem differs somewhat from a two-machine problem because of the larger number of possible solutions. Given the inertias and the phase angle of the $\mathbf{Y}_{ab}$ admittance in a two-machine problem, the maximum operating angle is completely determined, but in a three-machine problem the maximum operating angle between any two voltages is dependent upon the conditions at the third. The line of attack shall be to determine the phase position and magnitude of the internal voltages and then to apply the test for stability. In general, a three-machine problem possesses five

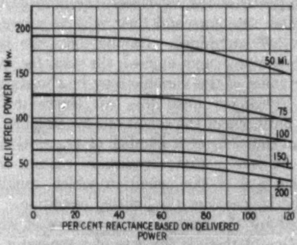

Fig. 18—Stability Limit of 110-Kv. Systems with Infinite Bus at Receiver

3-phase, 60-cycle, 4-0 copper, 13-ft. equivalent spacing degrees of freedom; after knowing the circuit constants it is necessary to know five additional quantities before the distribution of real and reactive power can be determined. These quantities might be three voltages and the angles between them or they might be three voltages, power at a point and the angle between two voltages. The intermediate condenser station problem may be cited as a particular example. Suppose the voltage be maintained constant at the terminals of the generator at the sending end, at the terminals of the condenser, and at the terminals of a generator at the receiving end. In addition suppose the power input into the system by the condenser will be zero. Under these conditions, one additional quantity permits of a solution of the operating condition. If the power supplied by the receiving end generator be fixed, the reactive power of that machine is also fixed; the real and reactive power of the sending end generator, the reactive power of the condenser, the internal voltages of all three machines and their relative phase angles, all, can be determined. Having fixed the last permissible variable and applied the test for stability, another value of the variable may be chosen and this process continued until the test shows instability; that is, until one of the conditions for stability fails.

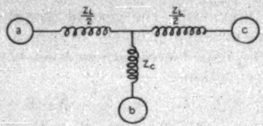

FIG. 19—CIRCUIT FOR SYMMETRICAL INTERMEDIATE CONDENSER CASE

The calculations of a number of practical cases including an intermediate condenser indicate that the relation $b > 0$ is the condition which usually fails first, that is, becomes the limiting condition. This is supported by the analysis of a number of simplified cases. One of these is the case of a generator, motor, and an intermediate condenser of zero impedance connected by reactive lines in which both the resistance in the lines and machines are neglected. It is interesting to note in connection with this particular case that the condition which must hold for the system to remain in a stable condition is dependent only upon the angle between the voltages and is independent of the inertias, the reactance of the circuit, the magnitude of the voltages and the location of the condenser. It will be shown in the next section that this condition also holds for the case in which the condenser impedance is finite and the system is symmetrical about the condenser.

Accepting this as the limiting condition, the following relation regarding inertias is obtained. The general form for $b$ is

$$b = (A-B-F)\ (C-D+E)+(D-F)\ (A-E) > 0 \quad (37)$$

Each of the terms denoted by $A, B, C$, etc., possess one value of inertia. After expanding, the expression $b$ can be arranged in three groups having $\frac{1}{W_a W_b}$, $\frac{1}{W_b W_c}$ and $\frac{1}{W_c W_a}$, respectively, for coefficients.

If the stored energy of all the machines is equal, the three coefficients are equal so that the limiting conditions become independent of inertia or if any one has an extremely large inertia, in the limit, say infinitely large, the power limit of the system is independent of the inertias of the other machines. Similarly, if the inertia of one machine is zero and the other two equal, the limit is independent of the values of the other two machines.

## INTERMEDIATE CONDENSER STATION PURE REACTANCE LINES

An example of the three-machine problem which is sufficiently simple to permit of mathematical analysis to determine which of the stability conditions will be controlling and from which important practical conclusions regarding static stability may be drawn is the case of a transmission system in which the resistance and charging current are neglected, with a condenser station located midway in the line. Assume a synchronous motor load whose characteristics are identical to those of the generator. Let $a$ be the generator, $b$ the condenser, and $c$ the motor, (see Fig. 19) and

$\mathbf{E}_A$ = Internal voltage of generator
$\mathbf{E}_B$ = Internal voltage of condenser
$\mathbf{E}_C$ = Internal voltage of motor
$\mathbf{E}_t$ = Terminal voltage of condenser
$\mathbf{Y}_{ab}$ = Admittance between $E_A$ and $E_B$
$\mathbf{Y}_{bc}$ = Admittance between $E_B$ and $E_C$
$\mathbf{Y}_{ac}$ = Admittance between $E_C$ and $E_A$
$\phi_x$ = Angular difference in rotor positions between $a$ and $b$, and $b$ and $c$.
$\mathbf{Z}_L$ = Line plus apparatus impedance between $E_a$ and $E_c$
$\mathbf{Z}_C$ = Impedance of condenser branch, *i. e.*, condenser and transformer.

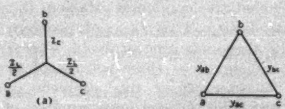

FIG. 20—STAR-DELTA TRANSFORMATION

By means of a simple delta-star conversion the network of Fig. 20A may be transformed into that of Fig. 20B in which

$$Y_{ab} = \frac{2}{Z_L + 4\,Z_C}$$

$$Y_{ac} = \frac{4\,Z_C}{Z_L\,(Z_L + 4\,Z_C)}$$

By assumption

$$\phi_1 = \phi_2 = \phi_3 = -\frac{\pi}{2}$$

$$W_c = W_a$$
$$E_C = E_A$$

The constants for the criteria of stability as developed in Appendix I will reduce to the following:

$$A = \frac{Y_{ab}\,E_A\,E_B}{W_b}\sin\left(\phi_x - \frac{\pi}{2}\right) = -\frac{Y_{ab}\,E_A\,E_B}{W_b}\cos\phi_x$$

$$B = \frac{Y_{ab}\,E_A\,E_B}{W_a}\sin\left(\phi_x + \frac{\pi}{2}\right) = \frac{Y_{ab}\,E_A\,E_B}{W_a}\cos\phi_x$$

$$C = \frac{Y_{ab}\,E_A\,E_B}{W_a}\sin\left(\phi_x - \frac{\pi}{2}\right)$$

$$= -\frac{Y_{ab}\,E_A\,E_B}{W_a}\cos\phi_x = -B$$

$$D = \frac{Y_{ab}\,E_A\,E_B}{W_b}\sin\left(\phi_x + \frac{\pi}{2}\right)$$

$$= \frac{Y_{ab}\,E_A\,E_B}{W_b}\cos\phi_x = -A$$

$$E = \frac{Y_{ac}\,E_A^2}{W_a}\sin\left(2\,\phi_x - \frac{\pi}{2}\right) = -\frac{Y_{ac}\,E_A^2}{W_a}\cos 2\,\phi_x$$

$$F = \frac{Y_{ac}\,E_A^2}{W_a}\sin\left(2\,\phi_x + \frac{\pi}{2}\right)$$

$$= \frac{Y_{ac}\,E_A^2}{W_a}\cos 2\,\phi_x = -E$$

The criteria for stability may now be determined

$$\underline{b > 0}$$

$$\begin{aligned} b &= K_1\,K_5 - K_2\,K_4 \\ &= (A + E - B)^2 - (-A + E)^2 \\ &= \frac{Y_{ab}^2\,E_A^2\,E_B^2}{W_a}\left[\frac{2}{W_b} + \frac{1}{W_a}\right]\cos\phi_x \end{aligned}$$

$$\left[\frac{2\,Y_{ac}\,E_A}{Y_{ab}\,E_B}\cos 2\,\phi_x + \cos\phi_x\right]$$

$$= \frac{2\,Y_{ac}\,Y_{ab}\,E_A^3\,E_B}{W_a}\left[\frac{2}{W_b} + \frac{1}{W_a}\right]\cos\phi_x$$

$$\left[\cos 2\,\phi_x + \frac{Z_L\,E_B}{4\,Z_C\,E_A}\cos\phi_x\right] >$$

$$\underline{a > 0}$$

$$\begin{aligned} a &= -(K_1 + K_5) \\ &= 2\,(-A + B - E) \\ &= \frac{2\,Y_{ac}\,Y_{ab}\,E_A^2}{W_a}\left[\cos 2\,\phi_x\right. \\ &\qquad \left. + \frac{1}{2}\,\frac{Z_L}{Z_C}\,\frac{E_B}{E_A}\left(1 + \frac{W_a}{W_b}\right)\cos\phi_x\right] > 0 \end{aligned}$$

$$\underline{a^2 - 4\,b > 0}$$

$$\begin{aligned} a^2 - 4\,b &= (K_1 + K_5)^2 - 4\,(K_1\,K_5 - K_2\,K_4) \\ &= (K_1 - K_5)^2 + 4\,K_2\,K_4 \\ &= (K_1 - K_5)^2 + (-\mathrm{A} + E)^2 > 0 \end{aligned}$$

Of the three conditions, the last is always fulfilled and may be dismissed. The other two conditions contain terms of the form

$$\cos 2\,\phi_x + M\cos\phi_x \qquad \textbf{(38)}$$

in which $M$ is the positive coefficient of $\cos\phi_x$. Examination of functions $a$ and $b$ indicate that the conditions fail when either $\cos\phi_x$ of function $b$ or one of the terms of form (**38**) in either function $a$ or $b$ equals zero. The limiting condition is that one for which this equality is true for the smallest angle. The term of the form (**38**) equals zero, depending upon the value of $M$, between $\pi/4 < \phi_x < \pi/2$ but $\cos\phi_x$ equals zero only at $\pi/2$. The discussion, therefore, narrows down to an examination of the two terms in $a$ and $b$ of the above form (**38**). This term may be written

$$2\cos^2\phi_x + M\cos\phi_x - 1 = 0 \qquad \textbf{(39)}$$

$$\cos\phi_x = \frac{-M \pm \sqrt{M^2 + 8}}{4} \qquad \textbf{(40)}$$

Examination of this equation shows that the smaller value of $\phi_x$ will be obtained for the smaller value of $M$. Since the $M$ constant for the $b$ condition is always smaller than that for the $a$ condition, in the ratio $\dfrac{1}{2\left(1 + \dfrac{W_a}{W_b}\right)}$, the $b$ condition is always the limiting one. The value of $M$ to be used is

$$M = \frac{Z_L}{4\,Z_C}\,\frac{E_B}{E_A} \qquad \textbf{(41)}$$

The direct application of this relation requires a knowledge of the internal voltage $E_B$, of the condenser which is not usually known. The usual practise is to regulate for constant voltage at the terminals of the machine or by means of a compensator on the high side of the condenser transformers. Using the latter assumption it can be shown by means of a power circle diagram that the kv-a. supplied by the condenser is

$$Q = \frac{4\,E_I^2}{Z_L} - \frac{4\,E_I\,E_A}{Z_L}\cos\phi_x \qquad (42)$$

The internal voltage of the condenser is then

$$E_B = E_I + Z_C\,\frac{Q}{E_I}$$

$$= E_I + \frac{4\,Z_C}{Z}\,E_I - \frac{4\,Z_C}{Z_L}\,E_A\cos\phi_x$$

or multiplying by $\dfrac{Z_L}{4\,Z_C\,E_A}$

$$\frac{Z_L}{4\,Z_C}\,\frac{E_B}{E_A} = M = \frac{1}{4}\left(\frac{Z_L}{Z_C} + 4\right)\frac{E_I}{E_A} - \cos\phi_x \qquad (43)$$

Substituting the values of $M$ from equation (43) in equation (39) permits a determination of $\cos\phi_x$ from which $\sin\phi_x$ may be plotted as a function of $\dfrac{Z_C}{Z_L}$ for the different values of $\dfrac{E_I}{E_A}$ as shown in Fig. 21. The quantity $\sin\phi_x$ gives a direct measure of the improvement in stability limit obtainable by virtue of the condenser. The power at $C$ is

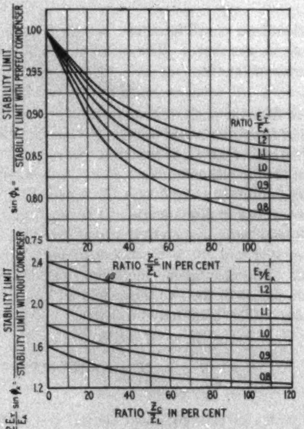

FIG. 21—EFFECT OF INTERMEDIATE CONDENSER ON STABILITY LIMIT

$$P_c = \frac{2\,E_I\,E_A}{Z_L}\sin\phi_x \qquad (44)$$

With a condenser of zero impedance the power limit is $2\,E_I\,E_A/Z_L$, so that the ratio of the power that can be transmitted with a finite condenser to that which can be transmitted with a condenser of zero impedance is $\sin\phi_x$.

The power limit of the line without an intermediate condenser station is $E_A^2/Z_L$. The improvement achieved by the intermediate condenser is then $2\,E_I\sin\phi_x/E_A$. This quantity is also plotted in Fig. 21.

In reviewing the properties of a system with an intermediate condenser it will be noted first that the stability limit for the symmetrical case is independent of the inertias. In addition it will be observed that a given condenser will show to better advantage on a long line than on a short line or expressed differently, a short line requires a condenser of lower impedance than a longer line to produce the same improvement.

## FOUR-MACHINE PROBLEM

The circuit conditions for the "four-machine" problem referred to previously are completely defined by the following equations:

$$\left.\begin{aligned}
\mathbf{I}_a &= \mathbf{Y}_{aa}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b - \mathbf{Y}_{ac}\,\mathbf{E}_c - \mathbf{Y}_{ad}\,\mathbf{E}_d\\
\mathbf{I}_b &= -\,\mathbf{Y}_{ba}\,\mathbf{E}_a + \mathbf{Y}_{bb}\,\mathbf{E}_b - \mathbf{Y}_{bc}\,\mathbf{E}_c - \mathbf{Y}_{bd}\,\mathbf{E}_d\\
\mathbf{I}_c &= -\,\mathbf{Y}_{ca}\,\mathbf{E}_a - \mathbf{Y}_{cb}\,\mathbf{E}_b + \mathbf{Y}_{cc}\,\mathbf{E}_c - \mathbf{Y}_{cd}\,\mathbf{E}_d\\
\mathbf{I}_d &= -\,\mathbf{Y}_{da}\,\mathbf{E}_a - \mathbf{Y}_{db}\,\mathbf{E}_b - \mathbf{Y}_{dc}\,\mathbf{E}_c + \mathbf{Y}_{dd}\,\mathbf{E}_d
\end{aligned}\right\} \qquad (45)$$

in which the $\mathbf{I}_a$, $\mathbf{I}_b$, $\mathbf{I}_c$, and $\mathbf{I}_d$ are line currents and $\mathbf{E}_a$, $\mathbf{E}_b$, $\mathbf{E}_c$, and $\mathbf{E}_d$ the voltages to neutral. As shown in the Appendix I the necessary conditions which must be fulfilled so that the system remains in synchronism are

$$\left.\begin{aligned}
c &> 0\\
b &> 0\\
a\,b - 9\,c &> 0\\
\Delta - b &> 0\\
a^2 - 3\,b &> 0
\end{aligned}\right\} \qquad (46)$$

in which $a$, $b$, $c$, and $\Delta$, defined in the Appendix, are functions of the circuit constants, system voltages, and inertias of the machines.

All of these conditions must be fulfilled simultaneously. The failure of any one is sufficient proof of instability. In problems of a given type one of them will be found to fail before the others and after establishing the particular one, it will be necessary to consider only this one condition.

The problem involving two intermediate condensers with synchronous machines at each end of the line has been chosen for discussion because of its important bearing on long distance power transmission. The condensers were assumed to have zero impedance and the resistance and charging current were neglected. Theoretical analysis of this case indicated that the $c$ condition was the limiting one. It further showed that the stability limit occurred when the angle between any two adjacent machine voltages became equal to $\pi/2$. This conclusion is independent of the inertia of the machines, of the magnitude of machine voltages and of the location of the condensers.

Calculations of stability limits of practical cases, the results of which will be given later, also indicated that the $c$ condition is controlling.

Assuming then that this condition will be limiting for all practical cases involving two intermediate condenser stations, interesting relations may be derived.

$$c = K_1 K_6 K_8 + K_2 K_4 K_9 + K_3 K_5 K_7 - K_1 K_5 K_9 - K_2 K_6 K_7 K_3 K_4 K_8 > 0 \qquad (47)$$

Since each of the $K$'s contains only one inertia term and $c$ is composed of groups of three, the terms can be expanded into four groups having for the coefficients the terms $\frac{1}{W_a W_b W_c}$, $\frac{1}{W_a W_b W_d}$, $\frac{1}{W_b W_c W_d}$, $\frac{1}{W_a W_c W_d}$, respectively. If one of the inertias be infinitely large three of the groups become zero so that the limit becomes independent of the inertias of the other machines. Other combinations for which the limit is independent of the inertias of the machines are:

1. All equal
2. One zero and other three equal
3. Two zero and other two equal.

## STABILITY LIMITS WITH INTERMEDIATE CONDENSER STATIONS

An important application of the theory and methods developed is for the determination of the stability limits of transmission systems with synchronous condenser stations located at intermediate points along the transmission line. This is of particular interest at this time because of its bearing on long distance power transmission. The problems involving one and two intermediate synchronous condensers are special cases of the three- and four-machine problems in which power input and output of the intermediate machines, except for losses, are made equal to zero.

Three general questions arise as to the intermediate condenser station under static conditions, namely, location, voltages to be maintained and condenser characteristics.

Location of one intermediate condenser for a symmetrical system is clearly at the midpoint of the series impedance of the system regardless of the characteristics of the condenser station itself. With two intermediate condensers the answer is less simple. With zero impedance on a symmetrical system the condensers should be located so as to divide the system into three equal sections. With finite condenser impedance the middle section should be of relatively less impedance than the end sections. With finite impedance condensers the variations from the best theoretical location will have relatively little effect on the stability limit, consequently power system layout need not be handicapped by a requirement to obtain the theoretically best location of condensers at intermediate points.

In regard to the voltages to be maintained there is, undoubtedly, an advantage in maintaining them at as high values as permissible without reduction of voltages at other points. Practically, this means that the voltage at condenser stations should be maintained on the high voltage line at the highest permissible value.

With respect to the characteristics of a condenser this subject can best be discussed by showing the results of calculations. The first case considered is that of one intermediate condenser located between the sending and receiving ends of 220-kv. transmission systems of various lengths. The sum of generator and transformer reactances was assumed in every case to be 12.5 per cent on 100,000 kv-a., and their resistances were neglected. The voltage was assumed to be maintained at 220 kv. on the high-voltage side of the transformers at the generating, receiving, and intermediate condenser stations. The best simple approximation of most of the receiving systems met in practise is the assumption of infinite capacity of the receiving end; that is, zero machine impedance and infinite inertia. It was shown in the discussion of the three-machine problem that when the inertia of one machine was infinite, static stability limits were independent of the inertia of the other two machines. In Fig. 22 are shown the results of calculations of the stability limits of transmission lines of various lengths plotted as a function of the reactance of the condenser and its transformer. In addition, the condenser capacity required at the stability limit is shown by the dotted lines. In estimating the stability limits of particular systems it will be found convenient to make use of the curves showing condenser capacity required at the stability limit in order to convert the impedance base from 100,000 kv-a. to the base corresponding to the capacity considered. At the right of Fig. 22 the following data are plotted:

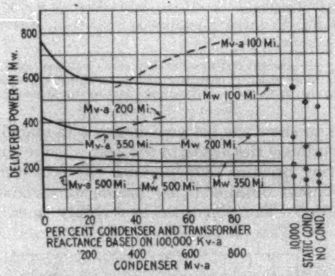

FIG. 22—STABILITY LIMIT OF 220-KV. LINES OF VARIOUS LENGTHS WITH ONE INTERMEDIATE CONDENSER STATION

3-phase, 60-cycle, 795,000-cir. mils aluminum condenser, steel reinforced, 29-ft. equivalent spacing, generator and transformer reactance, 12.5 per cent based on 100,000 kv-a. infinite bus and inertia at receiver

1. The stability limit of systems with condensers having the extremely high impedance of 10,000 per cent.

This corresponds to the condition of an essentially constant current condenser.

2. The stability limit of systems with variable capacity static condensers located at the same points as synchronous condensers. In this case the condenser capacity was made variable to maintain the transmission voltage constant at 220 kv.

3. The static stability limit of the line alone, that is, without any apparatus at the intermediate points.

In Fig. 23 the same data are plotted in a different manner to show the per cent increase in stability limit as a function of the length of the line. These curves are interesting because they indicate the relatively small improvement obtainable by means of variable static condensers. The difference in stability limit may be explained in a qualitative manner as being due to the variation of the reactive kv-a. with voltage for the different types of apparatus as illustrated in Fig. 24. It will be observed that the greater the increase in leading kv-a., the greater will be the stability limit.

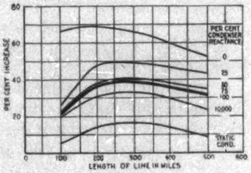

FIG. 23—INCREASE IN STABILITY LIMITS OF 220-KV. LINES OF VARIOUS LENGTHS OBTAINABLE BY ONE INTERMEDIATE CONDENSER STATION

3-phase, 60-cycle, 795,000-cir. mils aluminum condenser, steel reinforced, 29-ft. equivalent spacing, generator and transformer reactance 12.5 per cent based on 100,000 kv-a. Infinite bus and inertia at receiver

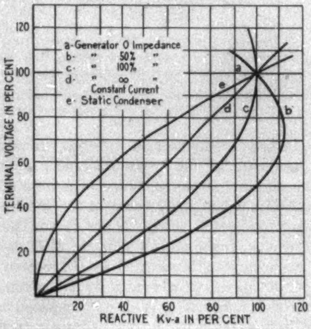

FIG. 24—VARIATION OF KV-A. WITH VOLTAGE OF SYNCHRONOUS CONDENSERS OF VARIOUS IMPEDANCE AND ALSO STATIC CONDENSERS

Similar calculations were made for the 350-mile line with two intermediate condenser stations instead of one with the results shown in Fig. 25. The increase in power limits obtainable by the installation of one and two condensers is shown in Fig. 26 which is plotted in the per cent increase in stability limit as a function of the condenser impedance. It will be observed that the curves which are plotted for the same total condenser capacity show that relatively less improvement is obtained by using the second condenser station.

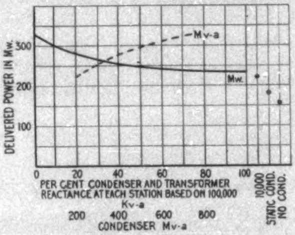

FIG. 25—VARIATION OF STABILITY LIMIT OF A 350-MI., 220-KV. LINE WITH CONDENSER IMPEDANCE

350-mi. line, 220-kv., 3-phase, 60-cycle, 795,000-cir. mils aluminum condenser, steel reinforced, 29-ft. equivalent spacing, generator and transformer reactance 12.5 per cent based on 100,000 kv-a. Infinite bus and inertia at receiver

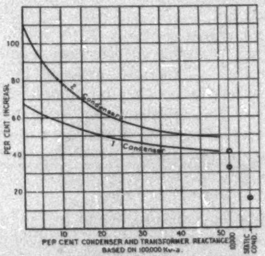

FIG. 26—INCREASE IN STABILITY LIMIT OBTAINABLE WITH ONE AND TWO INTERMEDIATE CONDENSER STATIONS

The curve assumes identical condenser characteristics for both cases, the total installed capacity being divided for the two-condenser case. 350-mi. line, 220-kv., 3-phase, 60-cycle, 795,000-cir. mils aluminum condenser, steel reinforced, 29 ft. equivalent spacing, generator and transformer reactance 12.5 per cent based on 100,000 kv-a. Infinite bus and inertia at receiver

## ACKNOWLEDGMENT

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## SUMMARY

The principal features of this paper may be summarized as follows:

For static stability calculations, power systems may be represented by a network with constant impedance and admittance branches with as many terminals as the number of synchronous machines requiring individual consideration. This method is justified because, as developed in the paper, loads may be represented by the equivalent constant admittances and synchronous machines may be replaced by their equivalent impedances.

A criterion for static stability of systems is presented together with formulas for the calculation of the two-, three- and four-machine cases.

It is shown that the maximum angle between machines for which synchronism can be maintained is, in general, somewhat dependent upon the inertia of the synchronous machines. Under some conditions synchronism can be maintained between two machines operating at angles greater than $\pi/2$. The delivered power corresponding to definite excitation of machines will, in general, be a maximum for a smaller angle than the maximum stable angle. While the investigations have shown that synchronism can be maintained in regions heretofore considered inherently unstable, operation in such regions is held to be inadvisable.

There are a number of generalizations which may be made as to the limiting stable condition.

For the two-machine problem the limiting angle is (*a*) $\pi/2$ when the inertias are equal, and (*b*) is greater or less than $\pi/2$ when the inertia of the receiving apparatus is greater or less than the inertia of the supply apparatus, respectively, and (*c*) is equal to $\pi/2$ and independent of inertia when resistance is negligible.

The limiting stable angle with one or two intermediate condensers of zero impedance and system resistance negligible is $\pi/2$ between adjacent sources of e. m. f. With finite-impedance condensers on a symmetrical system with resistance negligible the limiting angle is independent of the inertia of any of the machines.

The results of calculations of the stability of practical transmission lines indicate that large increases in static limits are obtainable with intermediate condensers. Small variation from the theoretically best location has relatively little influence on the stability limit. The improvement in stability due to an intermediate condenser is of course larger with low values of machine impedance but even a high-impedance condenser of the synchronous type will show marked advantage over static condensers which are unsuitable for this application.

## Appendix I

### DEVELOPMENT OF THE CRITERION FOR STABILITY FOUR-MACHINE PROBLEM

Problems involving four synchronous sources of e. m. f. such as synchronous generators, motors, and condensers have been termed "four-machine" problems. In the following, a criterion will be developed which when applied to a certain operating condition will enable one to determine whether the system is stable or unstable for that condition.

Consider the internal voltages of the four machines, constant and equal to $\mathbf{E}_a$, $\mathbf{E}_b$, $\mathbf{E}_c$, and $\mathbf{E}_d$, (to neutral) respectively. Regardless of the complexity of the system, assuming only that all loads and connecting networks may be considered as having characteristics of impedances, such as, resistors, inductors, and condensers, the current at the different machines may be expressed by the four following equations: (Impedances of machines are to be included as part of the network).

$$\left.\begin{aligned}
\mathbf{I}_a &= \mathbf{Y}_{aa}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b - \mathbf{Y}_{ac}\,\mathbf{E}_c - \mathbf{Y}_{ad}\,\mathbf{E}_d \\
\mathbf{I}_b &= -\mathbf{Y}_{ba}\,\mathbf{E}_a + \mathbf{Y}_{bb}\,\mathbf{E}_b - \mathbf{Y}_{bc}\,\mathbf{E}_c - \mathbf{Y}_{bd}\,\mathbf{E}_d \\
\mathbf{I}_c &= -\mathbf{Y}_{ca}\,\mathbf{E}_a - \mathbf{Y}_{cb}\,\mathbf{E}_b + \mathbf{Y}_{cc}\,\mathbf{E}_c - \mathbf{Y}_{cd}\,\mathbf{E}_d \\
\mathbf{I}_d &= -\mathbf{Y}_{da}\,\mathbf{E}_a - \mathbf{Y}_{db}\,\mathbf{E}_b - \mathbf{Y}_{dc}\,\mathbf{E}_c + \mathbf{Y}_{dd}\,\mathbf{E}_d
\end{aligned}\right\} \qquad \mathbf{(48)}$$

Letting the phase voltages be, respectively

$$\left.\begin{aligned}
\mathbf{E}_{\mathrm{A}} &= E_{\mathrm{A}}\,\epsilon^{j\phi a} \\
\mathbf{E}_{\mathrm{B}} &= E_{\mathrm{B}}\,\epsilon^{j\phi b} \\
\mathbf{E}_{\mathrm{C}} &= E_{\mathrm{C}}\,\epsilon^{j\phi c} \\
\mathbf{E}_{\mathrm{D}} &= E_{\mathrm{D}}\,\epsilon^{j\phi d}
\end{aligned}\right\} \qquad \mathbf{(49)}$$

and since

$$P_a + j\,Q_a = 3\,\mathbf{E}_a\,\mathfrak{I}_a \qquad \mathbf{(50)}$$

one may write:

$$\left.\begin{aligned}
P_a + j\,Q_a = {} & + \mathfrak{Y}_{aa}\,E_{\mathrm{A}}^2 - \mathfrak{Y}_{ab}\,E_{\mathrm{A}}\,E_{\mathrm{B}}\,\epsilon^{j(\phi a - \phi b)} \\
& - \mathfrak{Y}_{ac}\,E_{\mathrm{A}}\,E_{\mathrm{C}}\,\epsilon^{j(\phi a - \phi c)} - \mathfrak{Y}_{ad}\,E_{\mathrm{A}}\,E_{\mathrm{D}}\,\epsilon^{j(\phi a - \phi d)} \\
P_b + j\,Q_b = {} & - \mathfrak{Y}_{ba}\,E_{\mathrm{B}}\,E_{\mathrm{A}}\,\epsilon^{j(\phi b - \phi a)} + \mathfrak{Y}_{bb}\,E_b^2 \\
& - \mathfrak{Y}_{bc}\,E_{\mathrm{B}}\,E_{\mathrm{C}}\,\epsilon^{j(\phi b - \phi c)} - \mathfrak{Y}_{bd}\,E_{\mathrm{B}}\,E_{\mathrm{D}}\,\epsilon^{j(\phi b - \phi d)} \\
P_c + j\,Q_c = {} & - \mathfrak{Y}_{ca}\,E_{\mathrm{C}}\,E_{\mathrm{A}}\,\epsilon^{j(\phi c - \phi a)} \\
& - \mathfrak{Y}_{cb}\,E_{\mathrm{C}}\,E_{\mathrm{B}}\,\epsilon^{j(\phi c - \phi b)} + \mathfrak{Y}_{cc}\,E_c{}^2 \\
& - \mathfrak{Y}_{cd}\,E_{\mathrm{C}}\,E_{\mathrm{D}}\,\epsilon^{j(\phi c - \phi d)} \\
P_d + j\,Q_d = {} & - \mathfrak{Y}_{da}\,E_{\mathrm{D}}\,E_{\mathrm{A}}\,\epsilon^{j(\phi d - \phi a)} \\
& - \mathfrak{Y}_{db}\,E_{\mathrm{D}}\,E_{\mathrm{B}}\,\epsilon^{j(\phi d - \phi b)} \\
& - \mathfrak{Y}_{dc}\,E_{\mathrm{D}}\,E_{\mathrm{C}}\,\epsilon^{j(\phi d - \phi c)} + \mathfrak{Y}_{dd}\,E_{\mathrm{D}}^2
\end{aligned}\right\} \qquad \mathbf{(50)}$$

Now let

$$\left.\begin{aligned}
& & \phi_a - \phi_b &= \phi_x \\
& & \phi_b - \phi_c &= \phi_y \\
& & \phi_c - \phi_d &= \phi_z \\
&\text{and} & & \\
& & \mathbf{Y}_{ab} &= Y_{ab}\,\epsilon^{j\phi_1} \\
& & \mathbf{Y}_{bc} &= Y_{bc}\,\epsilon^{j\phi_2} \\
& & \mathbf{Y}_{ca} &= Y_{ca}\,\epsilon^{j\phi_3} \\
& & \mathbf{Y}_{ad} &= Y_{ad}\,\epsilon^{j\phi_4} \\
& & \mathbf{Y}_{bd} &= Y_{bd}\,\epsilon^{j\phi_5} \\
& & \mathbf{Y}_{cd} &= Y_{cd}\,\epsilon^{j\phi_6} \\
& & \mathbf{Y}_{aa} &= Y_{aa}\,\epsilon^{j\phi_7} \\
& & \mathbf{Y}_{bb} &= Y_{bb}\,\epsilon^{j\phi_8} \\
& & \mathbf{Y}_{cc} &= Y_{cc}\,\epsilon^{j\phi_9} \\
& & \mathbf{Y}_{dd} &= Y_{dd}\,\epsilon^{j\phi_{10}}
\end{aligned}\right\} \qquad \mathbf{(52)}$$

$$\left.\begin{aligned}
P_a &= Y_{aa} E_A^2 \cos \phi_7 - Y_{ab} E_A E_B \cos (\phi_x - \phi_1) \\
&\quad - Y_{ac} E_A E_C \cos (\phi_x + \phi_y - \phi_3) \\
&\qquad - Y_{ad} E_A E_D \cos (\phi_x + \phi_y + \phi_z - \phi_4) \\
P_b &= - Y_{ab} E_A E_B \cos (+ \phi_x + \phi_1) + Y_{bb} E_B^2 \cos \phi_8 \\
&\quad - Y_{bc} E_B E_C \cos (\phi_y - \phi_2) \\
&\qquad - Y_{bd} E_B E_D \cos (\phi_y + \phi_z - \phi_5 \\
P_c &= - Y_{ac} E_A E_C \cos (+ \phi_x + \phi_y + \phi_3) \\
&\qquad - Y_{bc} E_B E_C \cos (\phi_y + \phi_2) \\
&\quad + Y_{cc} E_C^2 \cos \phi_9 - Y_{cd} E_C E_D \cos (+ \phi_z - \phi_6) \\
P_d &= - Y_{ad} E_A E_D \cos (\phi_x + \phi_y + \phi_z + \phi_4) \\
&\qquad - Y_{bd} E_B E_D \cos (+ \phi_y + \phi_z + \phi_5) \\
&\quad - Y_{cd} E_C E_D \cos (\phi_z + \phi_6) + Y_{dd} E_D^2 \cos \phi_{10}
\end{aligned}\right\} \tag{53}$$

In analyzing the conditions for stable operation at a given operating point several criteria suggest themselves. One of the rotors can be displaced forcibly from its position of equilibrium and the relations analyzed to determine whether it will return to its original position. An increment of load could be placed on the shaft of one unit and the conditions investigated for stable operation. Another disturbance suggests itself in decreasing the network load by changing the network constants. The latter two involve a change in frequency or governor setting to determine the final steady state operating conditions. For this reason the change in angular position constituting the disturbing factor will be selected.

In any machine transient the difference between input and output power determines the power which must be supplied or absorbed by the rotor and consequently the deceleration or acceleration of the rotor and internal voltage. Governors are much too sluggish in action to rely upon their action to save the system from pulling out and for that reason one can consider the input constant. So that for constant governor settings $P_{ga}$, $P_{gb}$, $P_{gc}$, and $P_{gd}$, and stored mechanical energy $W_a$, $W_b$, $W_c$, and $W_d$ (in kw. sec. at synchronous speed) and using the relation $\alpha = \frac{180\,f}{W} \, \Delta P$, the corresponding accelerations may be written as follows:

$$\left.\begin{aligned}
\alpha_a &= \frac{180\,f}{W_a} [P_{ga} - P_a] \\
\alpha_b &= \frac{180\,f}{W_b} [P_{gb} - P_b] \\
\alpha_c &= \frac{180\,f}{W_c} [P_{gc} - P_c] \\
\alpha_d &= \frac{180\,f}{W_d} [P_{gd} - P_d]
\end{aligned}\right\} \tag{54}$$

In this investigation one is not interested as to whether the system as a whole will accelerate or decelerate which is determined by whether the sum of the governor settings $P_{ga}$, etc., is greater or less than the load, but rather in whether the system will pull apart. One is interested in the time rate of change of the difference in angles between the internal voltages, *i. e.*, in the time rate of change of $\phi_x$, $\phi_y$, and $\phi_z$.

But

$$\left.\begin{aligned}
\frac{d^2 \phi_x}{d t^2} &= \alpha_x = \alpha_a - \alpha_b \\
\frac{d^2 \phi_y}{d t^2} &= \alpha_y = \alpha_b - \alpha_c \\
\frac{d^2 \phi_z}{d t^2} &= \alpha_z = \alpha_c - \alpha_d
\end{aligned}\right\} \tag{55}$$

Therefore,

$$\begin{aligned}
\alpha_x = {} & \frac{180\,f}{W_a} P_{ga} - \frac{180\,f}{W_b} P_{gb} \\
& - \frac{180\,f}{W_a} Y_{aa} E_A^2 \cos \phi_7 + \frac{180\,f}{W_b} Y_{bb} E_B^2 \cos \phi_8 \\
& + \frac{180\,f}{W_a} [Y_{ab} E_A E_B \cos (\phi_x - \phi_1) \\
& \quad + Y_{ac} E_A E_C \cos (\phi_x + \phi_y - \phi_3) \\
& \quad + Y_{ad} E_A E_D \cos (\phi_x + \phi_y + \phi_z - \phi_4) ] \\
& - \frac{180\,f}{W_b} [Y_{ab} E_A E_B \cos (\phi_x + \phi_1) \\
& \quad + Y_{bc} E_B E_C \cos (\phi_y - \phi_2) \\
& \quad + Y_{bd} E_B E_D \cos (\phi_y + \phi_z - \phi_5) ]
\end{aligned} \tag{56}$$

$$\begin{aligned}
\alpha_y = {} & \frac{180\,f}{W_b} P_{gb} - \frac{180\,f}{W_c} P_{gc} \\
& - \frac{180\,f}{W_b} Y_{bb} E_B^2 \cos \phi_8 + \frac{180\,f}{W_c} Y_{cc} E_C^2 \cos \phi_9 \\
& + \frac{180\,f}{W_b} [Y_{ab} E_A E_B \cos (\phi_x + \phi_1) \\
& \quad + Y_{bc} E_B E_C \cos (\phi_y - \phi_2) \\
& \quad + Y_{bd} E_B E_D \cos (\phi_y + \phi_z - \phi_5) ] \\
& - \frac{180\,f}{W_c} [Y_{ac} E_A E_C \cos (\phi_x + \phi_y + \phi_3) \\
& \quad + Y_{bc} E_B E_C \cos (\phi_y + \phi_2) + Y_{cd} E_C E_D \cos (\phi_z - \phi_6)]
\end{aligned} \tag{57}$$

$$\begin{aligned}
\alpha_z = {} & \frac{180\,f}{W_c} P_{gc} - \frac{180\,f}{W_d} P_{gd} \\
& - \frac{180\,f}{W_c} Y_{cc} E_C^2 \cos \phi_9 + \frac{180\,f}{W_d} Y_{dd} E_D^2 \cos \phi_{10} \\
& + \frac{180\,f}{W_c} [Y_{ac} E_A E_C \cos (\phi_x + \phi_y + \phi_3)
\end{aligned}$$

$$
\begin{aligned}
&+ Y_{bc} E_B E_C (\phi_y + \phi_2) \\
&+ Y_{cd} E_C E_D \cos (\phi_z - \phi_6) ] \\
&- \frac{180 f}{W_d} [Y_{ad} E_A E_D \cos (\phi_x + \phi_y + \phi_z + \phi_4) \\
&+ Y_{bd} E_B E_D \cos (\phi_y + \phi_z + \phi_5) \\
&\qquad + Y_{cd} E_C E_D \cos (\phi_z + \phi_6) ] \qquad (58)
\end{aligned}
$$

These equations completely determine the oscillations between machines for the given circuit conditions, voltages, and governor settings. Each expression for acceleration $\frac{d^2 \phi_x}{d t^2}$ etc., is a complicated function of the angles $\phi_x$, $\phi_y$, and $\phi_z$ which are variable during the oscillations. No method is known whereby this type of oscillation can be calculated accurately by analytical methods. Step-by-step solutions are always possible. For small variations from the mean angles the following method may be used.

$$
\left.
\begin{aligned}
\Delta \alpha_x &= \frac{\partial \alpha_x}{\partial \phi_x} \Delta \phi_x + \frac{\partial \alpha_x}{\partial \phi_y} \Delta \phi_y + \frac{\partial \alpha_x}{\partial \phi_z} \Delta \phi_z \\
\Delta \alpha_y &= \frac{\partial \alpha_y}{\partial \phi_x} \Delta \phi_x + \frac{\partial \alpha_y}{\partial \phi_y} \Delta \phi_y + \frac{\partial \alpha_y}{\partial \phi_z} \Delta \phi_z \\
\Delta \alpha_z &= \frac{\partial \alpha_z}{\partial \phi_x} \Delta \phi_x + \frac{\partial \alpha_z}{\partial \phi_y} \Delta \phi_y + \frac{\partial \alpha_z}{\partial \phi_z} \Delta \phi_z
\end{aligned}
\right\} \quad (59)
$$

Let

$$
\left.
\begin{aligned}
&\frac{\partial \alpha_x}{\partial \phi_x} = K_1 \quad && \frac{\partial \alpha_y}{\partial \phi_x} = K_4 \quad && \frac{\partial \alpha_z}{\partial \phi_x} = K_7 \\
&\frac{\partial \alpha_x}{\partial \phi_y} = K_2 && \frac{\partial \alpha_y}{\partial \phi_y} = K_5 && \frac{\partial \alpha_z}{\partial \phi_y} = K_8 \\
&\frac{\partial \alpha_x}{\partial \phi_z} = K_3 && \frac{\partial \alpha_y}{\partial \phi_z} = K_6 && \frac{\partial \alpha_z}{\partial \phi_z} = K_9
\end{aligned}
\right\} \quad (60)
$$

then

$$
\left.
\begin{aligned}
\Delta \alpha_x &= K_1 \Delta \phi_x + K_2 \Delta \phi_y + K_3 \Delta \phi_z \\
\Delta \alpha_y &= K_4 \Delta \phi_x + K_5 \Delta \phi_y + K_6 \Delta \phi_z \\
\Delta \alpha_z &= K_7 \Delta \phi_x + K_8 \Delta \phi_y + K_9 \Delta \phi_z
\end{aligned}
\right\} \quad (61)
$$

If the mean angles during the oscillations, *i. e.*, the stationary values without oscillations be $\phi_{x0}$, $\phi_{y0}$, and $\phi_{z0}$, and the variations from these values be $\theta_x$, $\theta_y$, and $\theta_z$, then

$$
\left.
\begin{aligned}
\phi_x &= \phi_{x0} + \theta_x \\
\phi_y &= \phi_{y0} + \theta_y \\
\phi_z &= \phi_{z0} + \theta_z
\end{aligned}
\right\} \quad (62)
$$

or

$$
\left.
\begin{aligned}
\Delta \phi_x &= \theta_x \\
\Delta \phi_y &= \theta_y \\
\Delta \phi_z &= \theta_z
\end{aligned}
\right\} \quad (63)
$$

In addition

$$
\left.
\begin{aligned}
\alpha_x &= \frac{d^2 \phi_x}{d t^2} = \frac{d^2 \theta_x}{d t^2} \\
\alpha_y &\quad \frac{d^2 \phi_y}{d t^2} = \frac{d^2 \theta_y}{d t^2} \\
\alpha_z &= \frac{d^2 \phi_z}{d t^2} = \frac{d^2 \theta_z}{d t^2}
\end{aligned}
\right\} \quad (64)
$$

Since $\alpha_x$, $\alpha_y$ and $\alpha_z$, are equal to zero for steady conditions, *i. e.*, for

$$
\begin{aligned}
\phi_x &= \phi_{x0} \\
\phi_y &= \phi_{y0} \\
\phi_z &= \phi_{z0}
\end{aligned}
$$

one may write

$$
\left.
\begin{aligned}
\Delta \alpha_x &= \alpha_x \\
\Delta \alpha_y &= \alpha_y \\
\Delta \alpha_z &= \alpha_z
\end{aligned}
\right\} \quad (65)
$$

so that, substituting in the previous equations, (**61**), containing $K_1$, $K_2$, $K_3$, etc.

$$
\left.
\begin{aligned}
\frac{d^2 \theta_x}{d t^2} &= K_1 \theta_x + K_2 \theta_y + K_3 \theta_z \\
\frac{d^2 \theta_y}{d t^2} &= K_4 \theta_x + K_5 \theta_y + K_6 \theta_z \\
\frac{d^2 \theta_z}{d t^2} &= K_7 \theta_x + K_8 \theta_y + K_9 \theta_z
\end{aligned}
\right\} \quad (66)
$$

These simultaneous differential equations may be solved by, letting

$$
\left.
\begin{aligned}
\theta_x &= A \epsilon^{mt} \\
\theta_y &= B \epsilon^{mt} \\
\theta_z &= C \epsilon^{mt}
\end{aligned}
\right\} \quad (67)
$$

By substituting in equation (**66**)

$$
\left.
\begin{aligned}
m^2 A &= K_1 A + K_2 B + K_3 C \\
m^2 B &= K_4 A + K_5 B + K_6 C \\
m^2 C &= K_7 A + K_8 B + K_9 C
\end{aligned}
\right\} \quad (68)
$$

Rearranging

$$K_2 \frac{B}{A} + K_3 \frac{C}{A} + (K_1 - m^2) = 0$$

$$(K_5 - m^2) \frac{B}{A} + K_6 \frac{C}{A} = - K_4$$

$$K_8 \frac{B}{A} + (K_9 - m^2) \frac{C}{A} = - K_7$$

From the last two equations

$$
\frac{B}{A} = \frac{\begin{vmatrix} - K_4, & K_6 \\ - K_7, & (K_9 - m^2) \end{vmatrix}}{\begin{vmatrix} (K_5 - m^2), & K_6 \\ K_8, & (K_9 - m^2) \end{vmatrix}}
$$

$$\frac{C}{A} = \frac{\begin{vmatrix} (K_5 - m^2), - K_4 \\ K_8, - K_7 \end{vmatrix}}{\begin{vmatrix} (K_5 - m^2), K_6 \\ K_8, (K_9 - m^2) \end{vmatrix}}$$

Substituting these values of $\frac{B}{A}$ and $\frac{C}{A}$ in the first equation

$$K_2 \begin{vmatrix} - K_4, K_6 \\ - K_7, (K_9 - m^2) \end{vmatrix} + K_3 \begin{vmatrix} (K_5 - m^2), - K_4 \\ K_8, - K_7 \end{vmatrix} + (K_1 - m^2) \begin{vmatrix} (K_5 - m^2), K_6 \\ K_8, (K_9 - m^2) \end{vmatrix} = 0 \quad \mathbf{(69)}$$

Expanded this becomes a bi-cubic equation

$$m^6 + a\, m^4 + b\, m^2 + c = 0 \quad \mathbf{(70)}$$

in which

$$\left.\begin{array}{l} a = - (K_1 + K_5 + K_9) \\ b = K_1 K_5 + K_1 K_9 + K_5 K_9 - K_2 K_4 - K_3 K_7 - K_6 K_8 \\ c = K_1 K_6 K_8 + K_2 K_4 K_9 + K_3 K_5 K_7 - K_1 K_5 K_9 \\ \qquad - K_2 K_6 K_7 - K_3 K_4 K_8 \end{array}\right\} \quad \mathbf{(71)}$$

The condition that the system be stable for small disturbances such as the displacement of one or more rotors from its normal position is that all the roots of the cubic in $m^2$ be negative. In this case the six roots of the bi-cubic equation will be purely imaginary. Any disturbance results in an oscillation of constant amplitude. The formulas do not take damping into consideration, but from the physical consideration of the problem it is known that the oscillation will be damped out by copper losses, etc. If any of the roots of the cubic in $m^2$ are other than negative real numbers, either positive real or complex, one or more of the roots in $m$ will be of the form $(r + j\, s)$, $(r - j\, s)$, or $(r + j\, 0)$ in which $r$ is positive. This results in a term for $\theta_x$, $\theta_y$, and $\theta_z$ of the form $A\, \epsilon^{(r + js)t}$, $A\, \epsilon^{(r - js)t}$, or $A\, \epsilon^{rt}$. In any case the term increases indefinitely as a function of time.

The condition that all the roots of the cubic in $M^2$ be real and negative, requires that certain relations exist between the coefficients $a$, $b$, and $c$. This relation may be investigated by the application of Stürms theorem, from which the following conditions are obtained for the disturbance to be oscillatory, *i.e.*, for the system to be stable.

$$\left.\begin{array}{l} c > 0 \\ b > 0 \\ a\, b - 9\, c > 0 \\ \Delta - b > 0 \ldots (a\, b - 9\, c)\,(4\, a^3 - 15\, a\, b + 27\, c) \\ \qquad - 4\, b\, (a^2 - 3\, b)^2 > 0 \\ a^2 - 3\, b < 0 \end{array}\right\} \quad \mathbf{(72)}$$

The coefficients $a$, $b$, and $c$, are functions of $K_1$, $K_2$, $K_3$, etc., and the latter, functions of the angles $\phi_x$, $\phi_y$, and $\phi_z$. The $K$ coefficients will next be evaluated. Since $(180\, f)$ occurs as a coefficient of each $K$, it may be neglected. In what follows, therefore, the term $(180\, f)$ will be omitted.

$$K_1 = \frac{\partial\, \alpha_x}{\partial\, \phi_x} = - \frac{Y_{ab}\, E_A\, E_B}{W_a} \sin(\phi_x - \phi_1)$$

$$- \frac{Y_{ac}\, E_A\, E_C}{W_a} \sin(\phi_x + \phi_y - \phi_3)$$

$$- \frac{Y_{ad}\, E_A\, E_D}{W_a} \sin(\phi_x + \phi_y + \phi_z - \phi_4)$$

$$+ \frac{Y_{ab}\, E_A\, E_B}{W_b} \sin(\phi_x + \phi_1)$$

---

$$K_2 = \frac{\partial\, \alpha_x}{\partial\, \phi_y} = - \frac{Y_{ac}\, E_A\, E_C}{W_a} \sin(\phi_x + \phi_y - \phi_3)$$

$$- \frac{Y_{ad}\, E_A\, E_D}{W_a} \sin(\phi_x + \phi_y + \phi_z - \phi_4)$$

$$+ \frac{Y_{bc}\, E_B\, E_C}{W_b} \sin(\phi_y - \phi_2)$$

$$+ \frac{Y_{bd}\, E_B\, E_D}{W_b} \sin(\phi_y + \phi_z - \phi_5)$$

---

$$K_3 = \frac{\partial\, \alpha_x}{\partial\, \phi_z} = - \frac{Y_{ad}\, E_A\, E_D}{W_a} \sin(\phi_x + \phi_y + \phi_z - \phi_4)$$

$$+ \frac{Y_{bd}\, E_B\, E_D}{W_b} \sin(\phi_y + \phi_z - \phi_5)$$

---

$$K_4 = \frac{\partial\, \alpha_y}{\partial\, \phi_x} = - \frac{Y_{ab}\, E_A\, E_B}{W_b} \sin(\phi_x + \phi_1)$$

$$+ \frac{Y_{ac}\, E_A\, E_C}{W_c} \sin(\phi_x + \phi_y + \phi_3)$$

---

$$K_5 = \frac{\partial\, \alpha_y}{\partial\, \phi_y} = - \frac{Y_{bc}\, E_B\, E_C}{W_b} \sin(\phi_y - \phi_2)$$

$$- \frac{Y_{bd}\, E_B\, E_D}{W_b} \sin(\phi_y + \phi_z - \phi_5)$$

$$+ \frac{Y_{ac}\, E_A\, E_C}{W_c} \sin(\phi_x + \phi_y + \phi_3)$$

$$+ \frac{Y_{bc}\, E_B\, E_C}{W_c} \sin(\phi_y + \phi_2)$$

---

$$K_6 = \frac{\partial \alpha_y}{\partial \phi_z} = -\frac{Y_{bd} E_B E_D}{W_b} \sin(\phi_y + \phi_z - \phi_5) + \frac{Y_{cd} E_C E_D}{W_c} \sin(\phi_z - \phi_6)$$

---

$$K_7 = \frac{\partial \alpha_z}{\partial \phi_x} = -\frac{Y_{ac} E_A E_C}{W_c} \sin(\phi_x + \phi_y + \phi_3) + \frac{Y_{ad} E_A E_D}{W_d} \sin(\phi_x + \phi_y + \phi_z + \phi_4)$$

---

$$\begin{aligned} K_8 = \frac{\partial \alpha_z}{\partial \phi_y} = &-\frac{Y_{ac} E_A E_C}{W_c} \sin(\phi_x + \phi_y + \phi_3) \\ &- \frac{Y_{bc} E_B E_C}{W_c} \sin(\phi_y + \phi_2) \\ &+ \frac{Y_{ad} E_A E_D}{W_d} \sin(\phi_x + \phi_y + \phi_z + \phi_4) \\ &+ \frac{Y_{bd} E_B E_D}{W_d} \sin(\phi_y + \phi_z + \phi_5) \end{aligned}$$

---

$$\begin{aligned} K_9 = \frac{\partial \alpha_z}{\partial \phi_z} = &-\frac{Y_{cd} E_C E_D}{W_c} \sin(\phi_z - \phi_6) \\ &+ \frac{Y_{ad} E_A E_D}{W_d} \sin(\phi_x + \phi_y + \phi_z + \phi_4) \\ &+ \frac{Y_{bd} E_B E_D}{W_d} \sin(\phi_y + \phi_z + \phi_5) \\ &+ \frac{Y_{cd} E_C E_D}{W_d} \sin(\phi_z + \phi_6) \end{aligned}$$

---

Or letting

$$\left.\begin{aligned} A &= +\frac{Y_{ab} E_A E_B}{W_b} \sin(\phi_x + \phi_1) \\ B &= +\frac{Y_{ab} E_A E_B}{W_a} \sin(\phi_x - \phi_1) \\ C &= +\frac{Y_{bc} E_B E_C}{W_c} \sin(\phi_y + \phi_2) \\ D &= +\frac{Y_{bc} E_B E_C}{W_b} \sin(\phi_y - \phi_2) \\ E &= +\frac{Y_{ac} E_A E_C}{W_c} \sin(\phi_x + \phi_y + \phi_3) \end{aligned}\right\} \quad (73)$$

$$\left.\begin{aligned} F &= +\frac{Y_{ac} E_A E_C}{W_a} \sin(\phi_x + \phi_y - \phi_3) \\ G &= +\frac{Y_{cd} E_C E_D}{W_d} \sin(\phi_z + \phi_6) \\ H &= +\frac{Y_{cd} E_C E_D}{W_c} \sin(\phi_z - \phi_6) \\ I &= +\frac{Y_{bd} E_B E_D}{W_d} \sin(\phi_y + \phi_z + \phi_5) \\ J &= +\frac{Y_{bd} E_B E_D}{W_b} \sin(\phi_y + \phi_z - \phi_5) \\ K &= +\frac{Y_{ad} E_A E_D}{W_d} \sin(\phi_x + \phi_y + \phi_z + \phi_4) \\ L &= +\frac{Y_{ad} E_A E_D}{W_a} \sin(\phi_x + \phi_y + \phi_z - \phi_4) \end{aligned}\right\} \quad \begin{gathered}(73)\\ \text{Con-}\\ \text{tinued}\end{gathered}$$

$$\left.\begin{aligned} K_1 &= A - B - F - L \\ K_2 &= D - F + J - L \\ K_3 &= J - L \\ K_4 &= -A + E \\ K_5 &= C - D + E - J \\ K_6 &= H - J \\ K_7 &= -E + K \\ K_8 &= -C - E + I + K \\ K_9 &= G - H + I + K \end{aligned}\right\} \quad (74)$$

## THREE-MACHINE PROBLEM

The criterion for stability for a three-machine problem may be obtained almost directly from the results of the four-machine problem. The circuit conditions for this case are defined completely by the following equations.

$$\begin{aligned} \mathbf{I}_a &= \mathbf{Y}_{aa} \mathbf{E}_a - \mathbf{Y}_{ab} \mathbf{E}_b - \mathbf{Y}_{ac} \mathbf{E}_c \\ \mathbf{I}_b &= -\mathbf{Y}_{ba} \mathbf{E}_a + \mathbf{Y}_{bb} \mathbf{E}_b - \mathbf{Y}_{bc} \mathbf{E}_c \\ \mathbf{I}_c &= -\mathbf{Y}_{ca} \mathbf{E}_a - \mathbf{Y}_{cb} \mathbf{E}_b + \mathbf{Y}_{cc} \mathbf{E}_c \end{aligned}$$

Comparing these equations with those for the four-machine problem they will be seen to be identical if $\mathbf{Y}_{ad} = \mathbf{Y}_{bd} = \mathbf{Y}_{cd} = \mathbf{Y}_{dd} = 0$.

The corresponding values for the $K$ constants become

$$\left.\begin{aligned} K_1 &= A - B - F \\ K_2 &= D - F \\ K_3 &= 0 \\ K_4 &= -A + E \\ K_5 &= C - D + E \\ K_6 &= 0 \\ K_7 &= -E \\ K_8 &= -C - E \\ K_9 &= 0 \end{aligned}\right\} \quad (75)$$

On substitution of these values for the $K$ constants in equations (**71**), they reduce to

$$\left.\begin{aligned} a &= -(K_1 + K_5) \\ b &= K_1 K_5 - K_2 K_4 \\ c &= 0 \end{aligned}\right\} \qquad (\mathbf{76})$$

and since $c = 0$, equation (**70**) reduces to

$$M^4 + a M^2 + b = 0 \qquad (\mathbf{77})$$

The condition that the roots of this quadratic in $M^2$ be negative are that

$$\left.\begin{aligned} b &> 0 \\ a &> 0 \\ a^2 &> 4 b \end{aligned}\right\} \qquad (\mathbf{78})$$

### TWO-MACHINE PROBLEM

The results obtained previously for the two-machine problem in the body of the paper could have been obtained more simply but with probably less clearness by letting all the admittance coefficients but $\mathbf{Y}_{aa}$, $\mathbf{Y}_{bb}$, and $\mathbf{Y}_{ab}$ in equations (**48**) for the four-machine problem equal zero. After determining the $K$ constants and substituting them in the $a$, $b$, and $c$ constants, the resultant equation becomes

$$x^2 + a = 0 \qquad (\mathbf{79})$$

in which

$$a = -K_1 \qquad (\mathbf{80})$$

$$= -Y_{ab} E_A E_B \left[ \frac{1}{W_b} \sin(\phi_{x0} + \phi_1) - \frac{1}{W_a} \sin(\phi_{x0} - \phi_1) \right]$$

or the condition that operation be stable is that

$$\frac{1}{W_b} \sin(\phi_{x0} + \phi_1) - \frac{1}{W_a} \sin(\phi_{x0} - \phi_1) < 0$$

or that

$$\phi_{x0} < \tan^{-1} \frac{W_a + W_b}{W_b - W_a} \tan \phi_1 \qquad (\mathbf{81})$$

which checks results obtained by the more detailed method.

## Appendix II

### STATIC STABILITY LIMITS WITH LOADS THAT DO NOT VARY AS ORDINARY IMPEDANCES

Induction motors and synchronous motors, driving pumps, fans, etc., possess a load characteristic which is essentially one of constant shaft torque, or constant power; and lamp loads and converters vary as the square of the voltage. These loads can always be combined so that the composite result shows the variation of real power $P$ and reactive power $Q$ with voltage. The $\frac{dP}{dE}$ and $\frac{dQ}{DE}$ for the load may, therefore, be considered known. With fixed internal voltages (magnitude only) at $a$ and $b$ in Fig. 27 and the load at $C$, what is the criterion for system stability?

The currents at the three points $a$, $b$, and $c$ are connected by the following relations

$$\begin{aligned} \mathbf{I}_a &= \mathbf{Y}_{aa} \mathbf{E}_a - \mathbf{Y}_{ab} \mathbf{E}_b - \mathbf{Y}_{ac} \mathbf{E}_c \\ \mathbf{I}_b &= -\mathbf{Y}_{ab} \mathbf{E}_a + \mathbf{Y}_{bb} \mathbf{E}_b - \mathbf{Y}_{bc} \mathbf{E}_c \\ \mathbf{I}_c &= -\mathbf{Y}_{ca} \mathbf{E}_a - \mathbf{Y}_{bc} \mathbf{E}_b + \mathbf{Y}_{cc} \mathbf{E}_c \end{aligned}$$

Using the same notation as in the four-machine problem,

$$P_c = -Y_{ac} E_A E_C \cos(\phi_x + \phi_y + \phi_3) - Y_{bc} E_B E_C \cos(\phi_y + \phi_2) + Y_{cc} E_c^2 \cos \phi_9 \qquad (\mathbf{92})$$

$$Q_c = +Y_{ca} E_A E_C \sin(\phi_x + \phi_y + \phi_3) + Y_{bc} E_B E_C \sin(\phi_y + \phi_2) - Y_{cc} E_c^2 \sin \phi_9 \qquad (\mathbf{93})$$

Let

$$\begin{aligned} \phi_x &= \phi_{x0} + \theta_x \\ \phi_y &= \phi y_0 + \theta_y \\ E_c &= E_{c0} + e_c \\ P &= P_0 + p \\ Q &= Q_0 + q \end{aligned}$$

In which the terms with the zero subscript represents the mean values and the other term the variations for small oscillations.

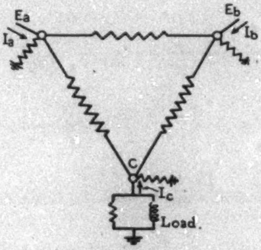

FIG. 27

For small values of $\theta_x$, $\theta_y$, and $e_c$

$$\Delta P = p = \frac{\partial P_c}{\partial \phi_x} \theta_x + \frac{\partial P_c}{\partial \phi_y} \theta_y + \frac{\partial P_c}{\partial E_c} e_c \qquad (\mathbf{94})$$

$$\begin{aligned} &= +Y_{ac} E_A E_C \sin(\phi_{x0} + \phi_{y0} + \phi_3) \,.\, \theta_x \\ &\quad + [+ Y_{ac} E_a E_c \sin(\phi_{x0} + \phi_{y0} + \phi_3) \\ &\qquad + Y_{bc} E_B E_C \sin(\phi_{y0} + \phi_2)] \,.\, \theta_y \\ &\quad + [- Y_{ac} E_A \cos(\phi_{x0} + \phi_{y0} + \phi_3) \\ &\qquad - Y_{bc} E_B \cos(\phi_{y0} + \phi_2) + 2 Y_{cc} E_C \cos \phi_9]\, e_c \end{aligned} \qquad (\mathbf{95})$$

or

$$= C_1 \theta_x + C_2 \theta_y + C_3 e_c \qquad (\mathbf{96})$$

Similarly

$$\Delta Q = q = \frac{\partial Q_c}{\partial \phi_x}\,\theta_x + \frac{\partial Q_c}{\partial \phi_y}\,\theta_y + \frac{\partial Q_c}{\partial E_c}\,e_c \qquad (97)$$

$$\begin{aligned} &= + Y_{ca} E_A E_C \cos(\phi_{x0} + \phi_{y0} + \phi_3)\,.\,\theta_x \\ &\quad + [Y_{ca} E_A E_C \cos(\phi_{x0} + \phi_{y0} + \phi_3) \\ &\qquad + Y_{bc} E_B E_C \cos(\phi_{y0} + \phi_2)\,]\,.\,\theta_y \\ &\quad + [Y_{ca} E_A \sin(\phi_{x0} + \phi_{y0} + \phi_3) \\ &\qquad + Y_{bc} E_B \sin(\phi_{y0} + \phi_2) - 2\,Y_{cc} E_C \sin\phi_9]\,e_c \qquad (98)\end{aligned}$$

or

$$= C_4\,\theta_x + C_5\,\theta_y + C_6\,e_c \qquad (99)$$

But $p$ and $q$ are also equal to:

$$p = \frac{d\,P_c}{d\,E_c}\,.\,e_c \qquad (100)$$

$$q = \frac{d\,Q_c}{d\,E_c}\,.\,e_c \qquad (101)$$

So that

$$\frac{d\,P_c}{d\,E_c}\,.\,e_c = C_1\,\theta_x + C_2\,\theta_y + C_3\,e_c \qquad (102)$$

$$\frac{d\,Q_c}{d\,E_c}\,.\,e_c = C_4\,\theta_x + C_5\,\theta_y + C_6\,e_c \qquad (103)$$

or

$$C_1\,\theta_x + C_2\,\theta_y + C_7\,e_c = 0 \qquad (104)$$

$$C_4\,\theta_x + C_5\,\theta_y + C_8\,e_c = 0 \qquad (105)$$

Solving these equations for $\theta_y$ and $e_c$

$$\theta_y = + \frac{C_4 C_7 - C_1 C_8}{C_2 C_8 - C_5 C_7}\,\theta_x \qquad (106)$$

$$e_c = \frac{C_1 C_5 - C_2 C_4}{C_2 C_8 - C_5 C_7}\,\theta_x \qquad (107)$$

Equation (56) under the discussion of the four-machine problem gives the relation for $\alpha_x$ applicable to this problem. For small variations in $\theta_x$, $\theta_y$, and $e_c$

$$\alpha_x = \frac{\partial \alpha_x}{\partial \phi_x}\,\theta_x + \frac{\partial \alpha_x}{\partial \phi_y}\,\theta_y + \frac{\partial \alpha_x}{\partial E_C}\,e_c \qquad (108)$$

$$= C_9\,\theta_x + C_{10}\,\theta_y + C_{11}\,e_c \qquad (109)$$

Substituting the above values of $\theta_y$ and $e_c$ from equations (106) and (107) in equation (109)

$$\alpha_x = \left[\, C_9 + C_{10}\,\frac{C_4 C_7 - C_1 C_8}{C_2 C_8 - C_5 C_7} + C_{11}\,\frac{C_1 C_5 - C_2 C_4}{C_2 C_8 - C_5 C_7}\right]\theta_x$$

$$\alpha_x = \frac{\begin{matrix} C_9 (C_2 C_8 - C_5 C_7) + C_{10} (C_4 C_7 - C_1 C_8) \\ + C_{11} (C_1 C_5 - C_2 C_4)\end{matrix}}{C_2 C_8 - C_5 C_7}\,\theta_x \qquad (110)$$

As long as the coefficient of $\theta_x$ is negative the system is stable. The limit will occur when it is equal to zero. Since the denominator can never equal infinity the limit occurs when

$$C_9 (C_2 C_8 - C_5 C_7) + C_{10} (C_4 C_7 - C_1 C_8) + C_{11} (C_1 C_5 - C_2 C_4) = 0 \qquad (111)$$

Resumé of coefficients:

$$C_1 = Y_{ac} E_A E_C \sin(\phi_{x0} + \phi_{y0} + \phi_3)$$

$$C_2 = Y_{ac} E_A E_C \sin(\phi_{x0} + \phi_{y0} + \phi_3) + Y_{bc} E_B E_C \sin(\phi_{y0} + \phi_2)$$

$$C_4 = Y_{ac} E_A E_C \cos(\phi_{x0} + \phi_{y0} + \phi_3)$$

$$C_5 = Y_{ac} E_A E_C \cos(\phi_{x0} + \phi_{y0} + \phi_3) + Y_{bc} E_B E_C \cos(\phi_{y0} + \phi_2)$$

$$\begin{aligned} C_7 &= C_3 - \frac{d\,P_c}{d\,E_c} \\ &= - Y_{ac} E_A \cos(\phi_{x0} + \phi_{y0} + \phi_3) \\ &\quad - Y_{bc} E_B \cos(\phi_{y0} + \phi_2) + 2\,Y_{cc} E_C \cos\phi_9 - \frac{d\,P_c}{d\,E_c} \\ &= \frac{P_c}{E_c} + Y_{cc} E_C \cos\phi_9 - \frac{d\,P_c}{d\,E_c}\end{aligned}$$

$$\begin{aligned} C_8 &= C_6 - \frac{d\,Q_c}{d\,E_c} \\ &= Y_{ca} E_A \sin(\phi_{x0} + \phi_{y0} + \phi_3) \\ &\quad + Y_{bc} E_B \sin(\phi_{y0} + \phi_2) - 2\,Y_{cc} E_C \sin\phi_9 - \frac{d\,Q_c}{d\,E_c} \\ &= \frac{Q_c}{E_c} - Y_{cc} E_C \sin\phi_9 - \frac{d\,Q_c}{d\,E_c}\end{aligned}$$

$$\begin{aligned} C_9 = &- \frac{Y_{ab}}{W_a} E_A E_B \sin(\phi_{x0} - \phi_1) \\ &- \frac{Y_{ac}}{W_a} E_A E_C \sin(\phi_{x0} + \phi_{y0} - \phi_3) \\ &+ \frac{Y_{ab}}{W_b} E_A E_B \sin(\phi_{x0} + \phi_1)\end{aligned}$$

$$\begin{aligned} C_{10} = &- \frac{Y_{ac}}{W_a} E_A E_C \sin(\phi_{x0} + \phi_{y0} - \phi_3) \\ &+ \frac{Y_{bc}}{W_b} E_B E_C \sin(\phi_{y0} - \phi_2)\end{aligned}$$

$$\begin{aligned} C_{11} = &\frac{Y_{ac}}{W_a} E_A \cos(\phi_{x0} + \phi_{y0} - \phi_3) \\ &- \frac{Y_{bc}}{W_b} E_B \cos(\phi_y - \phi_2)\end{aligned}$$

Stability limits were calculated for systems whose load characteristics are represented by the full lines in Fig. 7. These results were compared with similar calculations assuming the load characteristics were those of a constant shunt admittance as represented by the dotted line on the same figure. The first case investigated consisted of a simplified system form of the system in which the impedance connecting $a$ and $b$ is infinite, that connecting $b$ and $c$ $(0 + j\,100)$ ohms and that connecting $a$ and $c$ $(0 + j\,200)$ ohms. Voltage was assumed to be maintained at 220 kv. at $a$ and at $c$. Calculations were made for a large range of loads both positive and negative at $b$ and the results showed an extremely close agreement for stability limits for the two types of load characteristics, varying not more than 5 per cent for the extreme case. In addition similar calculations were made for a practical case in which line resistance and charging current were taken into consideration. The results indicated the same close agreement, from which it may be concluded that for all static stability calculations loads not containing large synchronous machines may be represented by shunt admittances of equivalent kv-a.

## Appendix III

### Derivation of Acceleration Equation

$$\alpha = \frac{180\,f}{E}\,\Delta P$$

Let

$\alpha$ = Acceleration
$T$ = Torque
$I$ = Moment of Inertia
$E$ = Stored energy
$P$ = Instantaneous power
$\omega$ = Angular velocity
$f$ = Frequency

In c. g. s. units

$$\alpha = \frac{T}{I}$$

$$\frac{T\,\omega^2}{2\left(\frac{1}{2}\,\omega^2 I\right)}$$

Since

$\frac{1}{2}\,\omega^2 I$ = Stored energy at any instant and

$T\,\omega$ = Instantaneous power $= P$

$$\alpha = \frac{\omega P}{2E} \text{ in mechanical rad. per sec. per sec.}$$

To this point $\alpha$ and $\omega$ have been expressed in mechanical radians. These may be converted to electrical radians by dividing both sides of the equation by the number of poles. But since these will cancel out the above expression is also true for $\alpha$ and $\omega$ expressed in electrical radians. Since

$$\begin{aligned} \omega &= \text{Angular vel. in electrical rad. per sec.} \\ &= 2\,\pi f \\ &= \frac{2\,\pi f\,360}{2\,\pi} \\ &= 360\,f \text{ degrees per sec.} \end{aligned}$$

Therefore

$$\alpha = \frac{180\,f}{E}\,P \text{ electrical degrees per sec. per sec.}$$

This expression is rigorously true using instantaneous values during a disturbance. A good approximation is to assume $f$ and $E$ constant and letting $\alpha$ vary only with $P$. For a 60 cycle system having a natural period of one second in which the total swing is 60 degrees the maximum error using this approximation is about 1 per cent.

For static stabilty calculations, however, since the departure from synchronism is inappreciable, the error introduced by this assumption is also inappreciable.

In the above formula if $E$ is expressed in watt-sec., $P$ should be expressed in watts and if $E$ is expressed in kilowatt-sec., $P$ should be expressed in kilowatts.

Conversion formula for $E$

$$E_{\text{in kw. sec.}} = 2.3\,(W\,R^2)\,(\text{R. P. M.})^2 \times 10^{-7}$$

$(W\,R^2)$ expressed in lb. ft.$^2$

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10. Mechanical Analogy to the Problem of Transmission Stability, by S. B. Griscom, *Electric Journal*, May, 1926.

11. The Baum Principle of Transmission, by C. L. Fortescue, *Electrical World*, May 7, 1927.

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15. *Synchronous Machines, I and II*, by Doherty and Nickle, JOURNAL A. I. E. E., Vol. XLV, page 974, October, 1926.

16. *Synchronous Machines III*, by Doherty and Nickle, JOURNAL of A. I. E. E., Sept., 1926, p. 887 and Aug., 1927, p. 827.

## Discussion

**F. E. Terman:** An illustration that indicates the thoroughness of the authors of this paper is their discovery of the fallacy of the classical belief that the maximum angle of stable operation of a network is the angle of maximum power of transmission. In reality the angle is a little greater, permitting stable operation slightly beyond the point of maximum power. The difference between the old and the correct belief is not great, but its discovery was a real achievement.

One of the most uncertain factors in stability computations is the characteristic of the load under change of voltage. Some investigators have assumed a load that drew constant power and reactive power as the load voltage changed (approximated by a motor load), while others have assumed that the load was such as to maintain the load voltage constant at all times (equivalent to assuming a receiving synchronous condenser of infinite capacity.) The former assumption gives computed results worse than are actually to be expected, and the latter leads to an optimistic result, considerably better than can be realized in practise. The actual load is one that allows the voltage to drop during disturbances, and as the voltage drops, the power demands of the load become less, and the power factor of the load improves. The power does not drop as fast as it would with a load consisting of an admittance of constant value, so that the admittance-load characteristic used by the authors is a correct assumption only in so far as the improvement of the power factor of the actual load can be considered as off-setting the less favorable power characteristic of the real load. When the voltage fluctuation is small it is likely that a constant-admittance load would give about the same result as a practical load, but for large fluctuations, as 25 per cent, this almost certainly would not be the case.

Actually, we don't know much regarding the reactive and real power drawn by the load when the voltage is suddenly changed. I should like to see some of the power people make tests, such as dropping the voltage at a distributing center first by 5 per cent, then 10 per cent, and so on, noting the change of power and power factor caused by each drop. Such information would be invaluable for stability studies, and could be obtained without creating an appreciable disturbance to service. At present we can get correct results for the conditions assumed, but we have very little idea how correct our assumptions are.

In applying the results of the paper to present transmission practise several points must be kept in mind. The results presented in Fig. 21, giving the effect of a midpoint condenser on the power limits neglect charging current, which is an important factor on lines over 200 mi. in length. In interpreting this figure, one must also remember that it is only the lower curves that apply to ordinary conditions. This is because the ratio of voltage at the midpoint of the line to the internal voltage of the generator (not terminal voltage) is normally less than unity. Boosting the midpoint voltage abnormally high by the use of a condenser is in effect increasing the average transmission voltage and this will obviously raise the power limit. The intermediate condenser when used to make the midpoint voltage higher than the terminal voltages will give the large increase in power limit shown by Fig. 21 in the upper curves, but this is gained at the expense of a poor voltage distribution along the line, and in a large measure could be obtained by the alternative method of omitting the condenser and raising the terminal voltages a little, thus keeping a flat voltage distribution. Such a flat distribution would not put as high a voltage on the midpoint of the line as would be present when the synchronous condensers were used.

Figs. 22 and 23 have been computed for an actual transmission line that has charging current, and indicate that a large intermediate condenser is required to raise the stability limit very much. An ordinary condenser has around 100 per cent synchronous reactance (*i. e.*, sustained short-circuit current equals full-load current). On the basis of this, the curve marked 100 per cent reactance represents an installed capacity of 100,000 kv-a. and the 25 per cent reactance curve represents 400,000-kv-a. installed capacity. An inspection of Figs. 22 and 23 indicates that an intermediate condenser in the order of hundreds of thousands of kv-a. is required to give large increases in the power that can be transmitted over the line.

Even with the use of large condensers, the gains that could be expected on an actual transmission system would be much less than indicated in Figs. 22 and 23 because these figures are based on the assumption of infinite-capacity bus at the receiver. An infinite bus is one which will keep its voltage absolutely constant during all kinds of system troubles, and no actual bus comes anywhere near being an infinite bus. Dr. Bush and Mr. Booth[1] made some computations which showed that condenser equipment giving about 40 per cent increase in limit under the assumption of infinite bus at the receiver, would give less than half of this gain in power limit with a finite bus approaching ordinary characteristics. There is a large difference between the actual finite bus and the theoretical infinite bus of the curves.

To sum up the situation, it is evident that this paper indicates that the increase of power limit that can be obtained by the use of intermediate synchronous condensers of usual characteristics is small unless the intermediate condenser has a capacity of at least 100,000 kv-a. and preferably two to four times this amount. Using standard condensers of 400,000 kv-a. capacity the increase in power limits with a finite receiver bus would probably be less than 40 per cent.

This is a discouragingly small gain for the price it costs. It seems that in all probability the next step lies in the development of low-impedance condensers used in conjunction with quick-excitation systems. A 100,000-kv-a. condenser having 10 per cent leakage reactance with an instantaneously acting exciting system would give the same increase of limits as a 1,000,000-kv-a. condenser of present standard type with the usual excitation speed. Such a condenser at the midpoint, with another at the receiving bus, would do wonders toward increasing the power limit of a transmission system. A condenser of this type at the receiver would give the practical equivalent of an infinite bus, and one at the midpoint would be substantially equivalent to a condenser of zero reactance. Fig. 23 shows that the gains would be very substantial.

**R. D. Evans:** With reference to Dr. Terman's discussion regarding the maximum angle for which systems are stable we did not wish to emphasize the point unduly because for commercial systems the increase is not very marked. However, when several synchronous machines are being considered it is very important to have the right type of limit. In this connection it may be observed that the maximum delivered power will in general occur for an angle less than the maximum stable angle; so that for practical calculations of power systems, the methods commonly in use are, according to our views, correct.

With respect to the discussion on the characteristics of the loads, we feel considerably more optimistic than Dr. Terman. We have made tests on our shop system in order to determine the variation of real power and reactive power for changes in the supply voltage and have found that the methods described in the paper apply. Also we have taken a number of power-company systems and segregated the load into relatively small units and studied their characteristics. We have found their variation of real power and reactive power with respect to voltage and combined them, and obtained the results described in Figs. 6 and 7. Finally, we have taken a static load, one of constant impedance, and analyzed it from a theoretical standpoint, considering the variation in real power and reactive power, with angle and voltage as worked out in Appendix II of the paper. For these conditions also the check was very good. Of course all who are interested in the theoretical calculations would welcome any kind of test which would give the fundamental experimental data on this subject.

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[1] TRANSACTIONS A. I. E. E., 1924, p. 72.

With respect to the curves showing the increase in power, I wish to emphasize the point, that the curves have been plotted on a conservative basis. For example, the condensers were not located at the theoretically most advantageous point, but were placed at the middle of the line regardless of the effect of the terminal equipment. The curves for 220 kv. and 110 kv., plotted in Figs. 15 and 18, are based on constant voltage on the high-voltage side, and no attempt was made to take advantage of any over-voltage.

There is another phase of this problem with respect to the static limits, which is important. The method and calculations as presented apply directly only to the limits that obtain with fixed excitation of the machines. It has been demonstrated that quick-response excitation systems under the control of suitable regulators will increase the loads which can be carried. This was first pointed out by E. B. Shand and first experimentally verified during 1925 by the authors of the present paper. We wish to make it clear that we have not included in the figures given in this paper any advantage which will accrue as a result of quick-response excitation systems.

**P. L. Alger:** There are two points in this paper that I wish to discuss. In the first place, the authors have concluded that under certain conditions, stability of a transmission line can be maintained beyond the impedance angle, and the exact limiting angle up to which stability can be maintained, depends upon the relative inertias of the sending and receiving-end machines.

This conclusion seems to be unreasonable, as the static stability limit is reached when the machines pull out of step so slowly that inertia effects should be negligible. What the authors have shown is that when the angle of maximum power is reached, and passed, the motor begins to slow down, the line current increases, and the generator also slows down until such time as the governor of the generator prime mover operates. If the generator inertia is sufficiently small, it will obviously retard faster than the motor, and the two ends of the line will stay in step at first. On the ninth page, the authors say—"The system as a whole will retard, reducing the frequency, but this will be taken care of by the automatic governors."

The fallacy in saying that the machines are stable beyond the angle of maximum power, lies in the assumption that the governor is able to reaccelerate the motor after it once has begun to slow down. What actually happens is that the motor and generator retard together until they have acquired an appreciably lower velocity than normal, and then the governor feeds more power to the prime mover, and the system breaks apart. The additional power reaccelerates the generator, and supplies additional power to the line, but this extra power is dissipated in extra copper losses, and the actual power received by the motor decreases. As the motor will not reaccelerate until it receives more than the power it had when it went out of step, and as it is impossible for the line to deliver more than the amount of power it did when the motor began to slow down, the motor can never be restored to speed, and so the system is unstable.

Thus, the authors have shown that when a system becomes unstable, the sending and receiving ends may stay in step while retarding up to the time the governor operates, instead of falling out of step immediately, as might have been thought. This conclusion is interesting, but is of no practical importance.

The second point that I should like to bring out is the matter of the additional condenser capacity required in order to secure a given additional amount of power over a transmission line. This ratio of additional kv-a. of installed condenser capacity to additional kw. output obtainable is the fundamental factor that determines whether the scheme of an intermediate condenser station is or is not of practical economic importance.

Fig. 21 of the paper presents curves showing the additional percentage output obtainable by using intermediate condensers, assuming a transmission line without resistance and without charging current. On this ideal basis they show that about 50 per cent additional kw. can be sent over a line by this means, on the basis of the reasonable values of $\frac{E_T}{E_A} = 0.9$, and $\frac{Z_C}{Z_L} = 0.6$. From equation (42), and the other data given, I calculate that this result is obtained by adding 200 per cent of the original line capacity in condensers. Or, in order to obtain each kilowatt of additional line capacity, it is necessary to add 4 kw. of condenser capacity. Under the different assumptions used in Fig. 22, approximately the same ratio is shown. Here, the authors have assumed no line losses, an infinite bus at the receiver, a very low generator reactance, and they have not stated clearly how they allowed for the important effects of the line charging currents.

Thus, the results of the paper indicate that under practical conditions it will be necessary to install much more than four times as much condenser capacity as there is obtained additional line capacity; and so it does not appear that the scheme of the intermediate condenser station is of great economic value at the present time.

In spite of my feelings that the results they have obtained are not of immediate practical importance, I feel that the authors have performed a great deal of useful work in their study of this important problem, and that their paper will be of great value as a basis for further study.

**R. D. Evans:** The question of the limiting stable angle is quite involved. The criterion selected was that the system be forcibly displaced slightly from the normal condition for which the mathematical solution of the voltage, power, and circuit conditions were satisfied. In order to determine whether or not the system pulls out at that point one must consider the transient and on account of the inertia and electrical loads one end tends to move more rapidly than the other. The possibility concerning which Mr. Alger is doubtful (if I understand him correctly), is the fact that if the angle is increased slightly the machine that is leading may tend to slow down more rapidly, and therefore to stay in step.

Concerning the question as to the effect of the governor, it is necessary only to point out that when the angle is decreased, more power can be transmitted.

With respect to the second point brought out by Mr. Alger, the amount of condenser kv-a. that has to be added to a system to increase the amount of power which can be transmitted, I do not know the exact basis used for his computations. If one considers the case of a system operating close to the static limit without a condenser and the ratio of the increase in reactive power to the increase in real power and then compares the corresponding conditions with a condenser operating near the static limit, it is true that one will obtain a relatively large increase of reactive kv-a. for each kilowatt increase.

The practical condition, however, is this: the system will be operated appreciably below static limit and under these conditions the increase in condenser capacity for each kilowatt of increased power which can be transmitted is not nearly so large as indicated by Mr. Alger. Furthermore, the total magnetizing kv-a. required by the system is actually less when supplied by machines which are distributed than when all condensers are at the receiving end. If the means for supplying reactive kv-a. are distributed an increase in the power limit is secured. So, for the practical conditions one can increase the power transmitted and also increase the margin of stability and thus arrive at the best compromise as to the increase of condenser capacity on the system and the amount of power to be transmitted, and in no event will one closely approach the static limits.

**R. W. Mackey:** (communicated after adjournment) The paper by Messrs. Wagner and Evans covers the cases of the static stability limits of straight-line transmission with one or two intermediate condenser stations, but where the system is more complicated or in the form of a network with condenser stations distributed on the network the mathematical method becomes cumbersome and practically impossible of solution.

The case I have in mind is the 220-kv. interconnection now being carried out in the east between the Philadelphia Electric Company, The Pennsylvania Power & Light Company, and the Public Service Gas & Electric Company of New Jersey.

During the last four months we have developed the mechanical model demonstrated by Mr. Evans for application to the quantitative solution of such complicated systems.

In the above case we were more concerned with the transient stability under short circuit and worst switching conditions than anything else but our solution also gave information as to static conditions.

I should like to elaborate on the methods used but this whole investigation is being prepared in the form of a paper to be presented by Messrs. Bergvall and Robinson.

At this time I mention this as it may be of interest for members to know that we are tackling the more complicated systems and expect to obtain great help from the analogous synchronous mechanical system.

**C. F. Wagner:** Dr. Terman's remarks regarding the increase in power occasioned by the use of an intermediate condenser station are substantially correct and in accord with our point of view. We concur with his remarks regarding the desirability of low-reactance condensers and quick-response excitation. In interpreting the curves showing the improvement on actual power systems, several facts must be born in mind. These results show the static limit of lines in which the amount of copper was dictated by loads considerably below the static limit, that is, for loads determined by the transient limit. If the static limit were determining, larger conductors would have been chosen for the line without condensers and still larger conductors for the line with condensers. A comparison under these conditions, paying due regard to the increased financial burden occasioned by larger conductors, would have been much more favorable for the intermediate condenser.

Mr. Alger questions our ideas regarding the limiting angle and states that our conclusions seem unreasonable to him. He cannot agree that the inertia has anything at all to do with the maximum angle at which the system can operate. Perhaps a discussion of a simple system consisting of a synchronous generator and synchronous motor with a connecting impedance in which the resistance is equal to the combined reactance of the line and machines, may clear this point. For the first case let the inertia of the generator be extremely large and the inertia of the motor, small. This corresponds to a small motor connected to a large system through an impedance. It is evident then that no action of the motor will be reflected in the main system. The power input into the motor will then increase until the angle reaches 45 deg., beyond which it will decrease. The limiting angle in this case is equal to the impedance angle. This is the more familiar arrangement and one from which the idea that the angle could not exceed the impedance angle was probably derived, but conclusions drawn from this illustration cannot be applied indiscriminately to other cases. Consider now that this synchronous motor is acting as a generator and is feeding power into the large system through such an impedance. Again, any phenomena in the generator will have an inappreciable effect upon the large system, whether it be voltage change or change in phase position of the rotors. With increasing angle the power input into the system will increase until an angle of 45 deg. is reached, beyond which the power will decrease. But what occurs to the output of the generator? This increases continuously even beyond 45 deg., reaching a maximum at 135 deg. While the input into the system decreases beyond 45 deg. the increase in copper loss is more than enough to overcome the decrease in system input. Now the generator responds, not to input into the system, but to its output. The system will be stable up to an angle at which an increase in angle no longer produces an increase in output, which in this case is 135 deg.

It is hoped that this discussion will make more lucid our conception of what occurs when the limiting angle is reached. While this discussion considered only limiting cases in which the inertia of one of the machines was extremely large it should be clear that for machines with more nearly equal inertias the difference in operation is one of degree only. These ideas have been verified by shop tests in which, citing from random, we have been able to obtain angles as large as 140 deg. No particular effort has been made to obtain larger angles.

I am at a loss to understand Mr. Alger's criticism of Fig. 22, when he states that no line losses were included in the calculations and we had not clearly stated how we had "allowed for the important effects of the line charging currents." The development of the formulas presented in the paper were premised on the most general type of circuit including both lumped and distributed constants. The general form of the equations are given in equations (1) and particular reference was made to distributed constants in the paragraph preceding equations (3). Mr. Alger's remarks regarding the efficacy of condensers should be tempered by the same considerations mentioned in the discussion of Dr. Terman and our reply. We do *not* agree with Mr. Alger that the scheme of the intermediate condenser station is not of great economic value at the present time, but on the contrary see wonderful possibility in its utility for the transmission of large blocks of power over great distances.

# Synchronous Condensers

BY P. L. ALGER[1]

Member, A. I. E. E.

***Synopsis.**—The paper reviews the general characteristics of large synchronous condensers, with particular reference to the possibilities of greater standardization in condenser specifications. Particular emphasis is placed on the question of the ratio of lagging to leading kv-a. capacity, and it is concluded that about 50 per cent lagging capacity is normal, while any important increase in this ratio requires special design of greater size and cost. Attention is called to the advantage to be gained by the use of reactors in place of such oversized condensers, where extra lagging capacity is needed. Separate sections of the paper are devoted to starting and stability characteristics, and to recent improvements in the design of synchronous condensers. Finally, the use of asynchronous condensers is discussed and found to be undesirable.*

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## I. OBJECT OF PAPER

THE large amounts of leading kv-a. required by modern power systems are most economically provided by means of synchronous condensers, and so the numbers and unit sizes of these machines have steadily increased in recent years. Thus, in 1925 two 40,000-kv-a., and this year the first of three 50,000-kv-a. condensers were placed in service on the Pacific Coast, while upwards of 35 others of sizes above 1000 kv-a. were built in the United States during 1926. Their continually increasing importance makes it desirable to simplify and standardize specifications for them as much as possible by eliminating unnecessary restrictions on their design. This paper is devoted to the description of some of these possibilities, and to the review of present practises in condenser design.

## II. PRINCIPAL CHARACTERISTICS OF SYNCHRONOUS CONDENSERS

The outstanding advantage of the synchronous condenser from an operating point of view, as compared with other means of supplying corrective kv-a., is the flexibility of its control. Once the machine is connected to the system, the reactive kv-a. it supplies can be varied continuously over the entire range from 50 per cent or more lagging to full leading kv-a., by simple adjustment of its field current. The adjustment can readily be made fully automatic, and so any desired condition, such as constancy of voltage or of power factor at a given point on the system, can be maintained.[2] This ease of adjustment also enables machines of very large size to be put on or taken off the system without appreciable disturbance. Thus, the economic advantages of large sizes can be fully realized with synchronous condensers.

Also, from the manufacturer's point of view, the synchronous condenser has an outstanding advantage over other rotating machines due to the fact that it neither drives nor is driven by any other apparatus. This permits a single, most economical, speed to be used for any given size, which, in turn, greatly helps standardization. Besides, the torque required being merely that to hold the rotor in step, the usual stability limitations of synchronous machines are lifted, and consequently very high current loadings can be employed. All these things contribute to the attainment of low costs. On the other hand, the low initial cost of the condenser itself and the small amount of associated equipment required combine to make the operating cost of the power losses an abnormally high proportion of the whole. On this account, special emphasis is placed on the attainment of low losses in synchronous condensers, and this factor tends to increase the initial cost.

## III. POSSIBILITIES OF STANDARDIZATION OF CONDENSER DESIGN

Ideal conditions for standardization combined with progress, exist when specifications are so drawn as to impose the least possible number of fixed requirements, and when contracts are awarded on the basis of the best performance on the non-fixed requirements. In this way, each manufacturer is given maximum freedom for the use of his available developments and for the play of his initiative. When more requirements than those absolutely necessary are laid down, all manufacturers are forced to do some things in the same way, with consequent inconvenience and increased developmental costs for some of them. Synchronous condensers much more nearly approach this ideal condition than most other types of rotating machines, and yet it seems that further progress in this direction can be made.

Aside from the restrictions imposed by the system frequency and by the method of rating employed, there are four variables that the purchaser may specify in describing a synchronous condenser. These are:

1. Leading kv-a. capacity, or rating,
2. Number of poles, or speed,
3. Voltage,
4. Ratio of lagging to leading kv-a. capacity.

The first of these is the fundamental variable that determines the size of the machine, so that the only possibility of standardization here is in the limitation of the number of ratings called for. Present practise in this respect is quite satisfactory, as the list of usual

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[1] A-c. Engineering Dept., General Electric Co., Schenectady, N. Y.

[2] Woodruff, "Principles of Electric Power Transmission," p. 153.

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ratings given in the first column of Table I has increments of at least 20 per cent, and intermediate ratings are seldom called for.

It is not desirable for the purchaser to specify the speed, as this limits the manufacturer's possibilities, and usually handicaps one more than another. The natural desire to improve his designs, and the economic urge of competition will cause each manufacturer to select the most economical speed for each machine, and the ultimate user has, therefore, nothing to gain by insisting on any particular value for it. As high-speed machines are lighter and more efficient than low-speed machines up to the points at which mechanical stresses and windage losses become limiting, it follows that synchronous condensers are normally built for high speeds. At the present time the speeds listed in Table I are customary, but the ratings at which the speed is changed vary slightly among different manufacturers. Usually, machines are guaranteed for 25 per cent overspeed.

Sometimes condensers are placed in substations in residential districts where quiet operation is essential, and this has been thought to require machines of lower than standard speeds. However, it is possible to so enclose a high-speed condenser as to make it satisfactorily quiet at less cost, and with better performance than can be obtained by using a speed below standard.

TABLE I
MOST ECONOMICAL SPEEDS AND VOLTAGES OF LARGE SYNCHRONOUS CONDENSERS

| Kv-a rating | 60 cycle, r. p. m. | Voltage |
|---|---|---|
| 500 | 1,200 | 2,400/4,150 |
| 750 | 1,200 | 2,400/4,150 |
| 1,000 | 1,200 | 2,400/4,150 |
| 1,500 | 1,200 | 2,400/4,150 |
| 2,000 | 900 | 2,400/4,150 |
| 3,000 | 900 | 2,400/4,150 |
| 4,000 | 900 | 2,400/4,150 |
| 5,000 | 900 | 6,900 or 11,500 |
| 7,500 | 900 | 6,900 or 11,500 |
| 10,000 | 900 | 6,900 or 11,500 |
| 15,000 | 720 or 900 | 11,500 or 13,800 |
| 20,000 | 720 | 11,500 or 13,800 |
| 25,000 | 600 or 720 | 11,500 or 13,800 |
| 30,000 | 600 | 13,800 |
| 40,000 | 600 | 13,800 |
| 50,000 | 600 | 13,800 |

For large sizes, it is often economical to use a completely closed system of ventilation with water coolers, as described in section VIII. If this is not desired, it is still possible to reduce the noise to a very small amount by using a standard enclosed machine with the addition of an air discharge chimney on top. Felt covered baffles can be so placed in this chimney as to practically eliminate the high pitched part of the noise without impeding the air flow to an important extent.

The voltage situation is not so simple as that of the speed, as there are so many different system voltages employed. However, the recent conferences on the subject, at New York and Niagara Falls (culminating in the new N. E. L. A. table of preferred standard voltages), give promise of some improvement. Also, as synchronous condensers are frequently provided with their own transformers or are fed from special tertiary transformer windings, it is often possible to choose the voltage that gives the most economical design. If the condenser voltage is too high, excessive insulation costs, and extra losses due to the large slots required will result; while if it is too low, excessive costs for the high current-carrying capacity and extra losses due to eddy currents in the massive conductors will arise. Hence, there is a most economical voltage for every rating, values of which are indicated in the third column of Table I.

In practise, the cost advantages of standardization are greater than those secured by selecting the ideally correct voltage, so that only the standard voltages nearest the ideal value are given in the table. It is customary to make the smaller machines suitable for either Y or delta connection.

The remaining variable is the ratio of lagging to leading kv-a. capacity. When a condenser is to be used solely for power-factor correction, to compensate for the lagging kv-a. of an industrial load, the lagging kv-a. capacity is of no direct interest, and so, in these cases, it is rightly left for the manufacturer to settle. As a value of the ratio not far from 0.5 gives the most economical design for leading power-factor operation, this is the value characteristic of most standard condensers. However, when condensers are to be used for voltage regulation, a considerable lagging kv-a. capacity is useful to hold the voltage down at light loads, and so, purchasers frequently specify a value of unity for this ratio. This imposes a considerable handicap on the designer and requires a special machine so that it is desirable to find some other way to obtain the desired results. It is worth while to study this question at some length, so the effects on design of varying this lag/lead ratio will first be described, and then methods of securing the desired operating results with normal condensers will be considered.

## IV. Lagging Kv-a. Capacity Secured by Changes in Condenser Design

The line current of a synchronous condenser is always equal to the difference between the voltage induced by its field and the impressed voltage divided by its synchronous reactance and corrected for saturation. Over-excitation of the field produces a leading current, and under-excitation produces a lagging current. The maximum possible lagging current occurs with zero field current, and is therefore equal to the line voltage divided by the synchronous reactance. While stable operation with a small reversed field excitation is possible, the trouble of providing for this reversal and the attendant increased likelihood of the condenser's falling out of synchronism make it inadvisable. For our purposes, therefore, the ratio of maximum lagging to normal leading kv-a. capacity of a synchronous condenser may be taken equal to the reciprocal of the per cent synchronous reactance, or to:

$$\text{Per cent maximum lagging kv-a.} = \frac{100}{X_s} = 100\, Y_s \qquad (1)$$

As lagging kv-a. are supplied when the field is under-excited, under this condition, the saturation of the magnetic circuit is slight and may be neglected. On the other hand, the leading kv-a. are supplied when the field is over-excited, a condition in which saturation of the magnetic circuit is pronounced.

If the ratio of the actual field excitation to the no-load air-gap excitation is represented by $F$, the per cent leading kv-a. is determined by the equation:

$$\text{Per cent leading kv-a.} < 100\,(F - 1)\, Y_s \qquad (2)$$

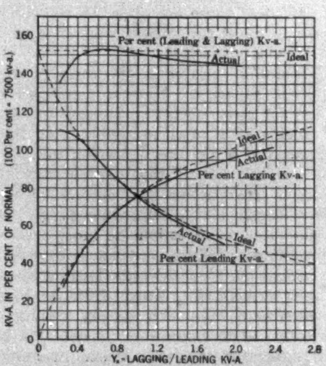

FIG. 1—RELATIVE LEADING AND LAGGING KV-A. CAPACITIES OF A 7500-KV-A., 900-REV. PER MIN. SYNCHRONOUS CONDENSER WITH VARYING AIR-GAP LENGTHS

Without saturation, the inequality sign becomes an equality sign, so that (**2**) reduces to (**1**), if $F$ is made equal to zero. Adding (**1**) and (**2**), the sum of the leading and lagging kv-a. is found to be,

$$\text{Per cent (leading + lagging kv-a.)} < 100\, F\, Y_s$$

$$= 100\, \frac{\text{rated field current}}{\text{S. C. field current}} \qquad (3)$$

Equation (**3**) indicates that the sum of the leading and lagging kv-a. capacities of a given machine is nearly independent of the no-load excitation. At full leading kv-a., (**2**) becomes equal to unity, so that the relation between $F$ and $Y_s$ is found to be,

$$\frac{\text{No-load air-gap field current}}{\text{Full-load field current}} = \frac{1}{F} < \frac{Y_s}{1 + Y_s} \qquad (4)$$

Equations (**1**), (**2**), and (**3**) are plotted in Fig. 1 as functions of $Y_s$. The dotted curves show the ideal conditions in the absence of saturation, while the solid curves show the actual conditions for a particular 7500-kv-a., 900-rev. per. min. condenser with different lengths of air-gap but with constant field excitation. The figure clearly indicates the sacrifice in leading kv-a. capacity necessary to secure greater lagging kv-a. If, instead of merely varying the air-gap, keeping the same stator, the entire design is changed always to keep the current carrying capacity of the stator winding just adequate for the maximum kv-a., slightly greater output can be obtained. For example, at a 100 per cent ratio of lagging to leading kv-a., a complete redesign will enable 83 per cent of normal leading kv-a. to be obtained as compared with only 75 per cent when the air-gap alone is changed. The more extensive changes, however, make the machine more special and require additional developmental charges, so that they are not always of economic advantage.

These results may be summarized by the statement that a synchronous condenser of a given size and cost may be designed to give any one of the four following combinations of leading and lagging kv-a. capacities:

| | |
|---|---|
| Standard................ | 100% leading, 50% lagging |
| Semi-standard............ | 90% leading, 65% lagging |
| Semi-standard............ | 75% leading, 75% lagging |
| Special.................... | 83% leading, 83% lagging |

Of course, these figures are only approximate, and the use of the nearest standard ratings, and of available design parts, will give rise to considerable variations. Nevertheless, they show the true effects, over a standard line of condensers, of different specifications for $Y_s$.

It is not worthwhile here to study the detail design differences between machines with various values of $Y_s$, but it is desirable to clearly realize the reasons for the reduction of rating that accompanies an increase in it. If a standard condenser is to be given an increased lagging capacity, without increase in size or cost, its air-gap must be lengthened. This entails a corresponding reduction in winding space on either rotor or stator and increases the field leakage, though it slightly decreases the armature leakage reactance and the pole-face losses. On the other hand, it is not practical to secure an increased leading kv-a. rating by reducing the lagging capacity below about 50 per cent because the air-gap excitation is already small compared with the total, and even a large reduction in the air-gap length will only make a slight gain. Further, when the gap is very small, excessive increases in armature reactance and in pole-face losses occur.

These facts have long been appreciated by designers,[3] but it is believed that they are not generally understood and that they deserve greater emphasis than they have heretofore received.

So far, we have merely shown that there is a definite decrease in kv-a. rating of a given machine if $Y_s$ is increased. There is also a distinct handicap in losses in leading kv-a. operation imposed by a wide departure from the normal value of $Y_s$. In Fig. 2, for example, there are shown the per cent losses of the same 7500-kv-a., 900-rev. per. min., synchronous condenser used in making Fig. 1. The curves show the expected full-load losses with different air-gaps, but the same stator, for both lagging and leading operation, as percentages of the kv-a. under each condition. These values of kv-a. are shown by the solid curves of Fig. 1. Redesigning the entire machine to obtain the best possible design for each length of air-gap does not materially reduce the losses, as shown by the points plotted at 100 per cent $Y_s$.

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[3] Reference Nos. 6, 9.

We, therefore, conclude that it is desirable to keep the value of $Y_s$ between 0.5 and 0.6 for a standard line of synchronous condensers. Wide departures from this range increase both costs and losses and so cannot be considered standard, and keeping closely to it will greatly facilitate standardization and will tend to further reduce costs and improve performance.

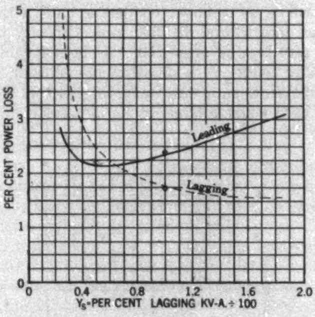

Fig. 2—Relative Full-Load Losses of a 7500-Kv-a., 900-Rev. Per Min. Synchronous Condenser with Varying Air-Gap Lengths

The desirability of this fixation of the value of $Y_s$ from the cost and efficiency viewpoints being established, it remains to consider it from the operating viewpoint.

## V. Other Methods of Securing Lagging Kv-a. Capacity

There are four principal methods of securing lagging kv-a. capacity without departing from normal condenser designs:

1. By reconnection of the condenser windings,
2. By raising the condenser voltage by means of transformer taps,
3. By use of reactors, and
4. By reduction of the system voltage.

The simplest general method of reconnection is to divide each phase in halves and connect unlike halves in series for lagging power-factor operation. On three phase, this is equivalent to increasing the voltage in the ratio of $2/\sqrt{3}$, and so it raises the lagging capacity to 4/3 of its normal value. However, unless rather complicated internal connections are made, the scheme considerably increases the short-circuit core losses.[4] In special cases, it is possible to change the number of circuits, and it is always possible to bring out taps from the winding in such a way that some of the armature coils can be cut out, with similar effects. These schemes however, all involve rather expensive switching arrangements, and they are not conveniently adaptable to automatic operation; also, they all result in increased losses per kv-a., so that from this point of view they are not attractive. Some of the methods are desirable for use in special cases, such as when a single machine is to be operated at different times on circuits of different frequencies, but they cannot be recommended for standard practise. At best, it is not practicable to double the lagging kv-a. capacity of a condenser by such means, so that they cannot completely solve the problem.

The recent developments in tap changing transformers[5] at first sight give promise of a solution by enabling the voltage to be varied at will over a wide range, without opening the circuit. However, on closer scrutiny, this possibility too is seen to be chimerical. In the first place, the tap changing apparatus is quite expensive, and the cost of the condenser is considerably increased by the necessity for insulating it for the highest voltage used. These extra costs alone are about the same as the extra cost of making the original condenser good for full-lagging capacity, and, in the second place, the losses in lagging power-factor operation are considerably increased by this arrangement as compared with the latter scheme.

In Fig. 3 there are shown curves of leading and lagging kv-a. capacity and per cent losses as functions of the impressed voltage, for the same 7500-kv-a., 900-rev. per. min., 11,000-volt condenser used in the previous figures. A voltage of about 130 per cent is required to give 90 per cent of rated kv-a. in lagging operation, at which point the losses are 2.2 per cent as compared with only 1.6 per cent for the oversized condenser built with a large enough air-gap to give the same lagging capacity (Fig. 2 at $Y_s = 1.55$). The curves show that no appreciable increase in leading kv-a. capacity can be secured by reducing the voltage, so that there is no incidental gain from this source to offset the disadvantages in lagging operation. We conclude, therefore, that the voltage regulation scheme is not of value for our purpose.

There remains the scheme of supplementing the deficient lagging kv-a. capacity of the standard synchronous condenser by the addition of parallel-connected reactors. As high-voltage air core reactors can now be built at costs per kv-a. which are about half those of synchronous condensers and with total losses of only about 1 per cent, this idea looks promising. The obvious objection to it is that it requires additional apparatus with suitable control and extra floor space.

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[4] Reference No. 6 and Q. Graham, *M. M. F. Wave of Polyphase Windings*, Journal A. I. E. E., February 1927, p. 118.

[5] A. Palme, *Application and Design of Load Ratio-Control Equipment*, presented at the Regional Meeting of District No. 1 of the A. I. E. E., Pittsfield, Mass., May 25-28, 1927.

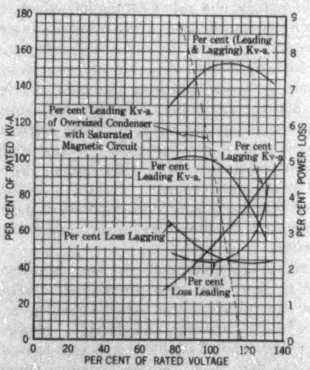

Fig. 3—Relative Characteristics of a 7500-Kv-a., 900-Rev. Per Min. Synchronous Condenser in Variable Voltage Operation

Furthermore, unless the reactors are to be thrown on the line all in one unit, expensive sectionalizing switches are required. Thus, the complete equipment is more expensive than a single oversized condenser designed for full lagging capacity.

The comparison of kv-a. ratings obtainable for the same cost, given in part IV, show that a standard condenser has 4/3 the leading kv-a. and half the lagging kv-a. ratings of an equivalent special condenser with 100 per cent lagging capacity. Taking the cost per leading kv-a. of the standard condenser as 1, and that of a reactor as ½, the total cost of the standard condenser plus sufficient reactors to give full lagging capacity is 1.25, while the cost of the special condenser is 1.33. These figures are rough, and they will be changed considerably by the addition of the extra equipment necessary, but they show that the costs of the two schemes are not widely different.

In the long run, however, the capital cost of the reactor scheme may prove to be the lower, for lagging kv-a. are principally required when a system is lightly loaded, in order to keep down the no-load voltage. Over a period of time, as the system load increases, the times of light load become shorter, and the minimum load becomes greater, so that less lagging kv-a. are required, and the demand comes to be for leading kv-a. capacity to hold the voltage up during overloads. Hence in some cases, it should be economical to install reactors alone when a transmission line is first built, later to add standard condensers, and finally to take the reactors away altogether for use at some other place, or for sale.

One of the chief reasons for specifying condensers with large lagging capacities seems to be the desire to make ample provision for the lagging kv-a. requirements in case these are greater than estimated. In such cases, it is often found that the extra lagging capacity is not actually needed. If, therefore, it is realized that additional lagging kv-a. can be secured at any later time on an economical basis by adding reactors, it will be possible to purchase initially condensers that have a lagging kv-a. capacity only equal to the estimated requirements, for which standard machines are usually adequate.

From the point of view of power losses, too, the reactor scheme may be attractive. Fig. 4 shows the total losses in per cent of kv-a. output for the combination of the standard 7500-kv-a. condenser used in the previous figures with sufficient air-core reactors to give a total of 100 per cent lagging capacity; together with a similar curve for a larger condenser built with a sufficient air-gap to give it 7500 kv-a. capacity on both leading and lagging operation. At light lagging loads the smaller condenser is slightly more efficient, while if the condenser is shut down and the reactors alone are used at light loads, a large saving in losses results. At medium loads the larger condenser has a little lower losses, but at full lagging kv-a. the combined unit gives better results. The variations are sufficiently small, however, to make the balance depend upon the operating schedules.

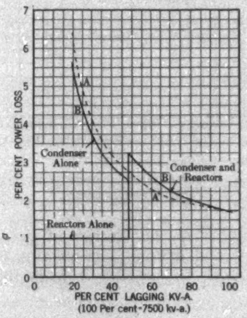

Fig. 4—Relative Power Losses in Lagging Kv-a. Generation

**A. Special synchronous condenser with 100 per cent lagging kv-a. capacity**

**B. Standard synchronous condenser with 52 per cent lagging kv-a. capacity and 48 per cent kv-a. of reactors**

All these methods of securing extra lagging capacity involve extra cost and losses, so that it is desirable to avoid the difficulties by merely reducing the system voltage. This reduces the leading kv-a. supplied by the transmission line capacity, and increases the lagging kv-a. due to the line reactance, thus greatly decreasing the lagging requirements. The voltage reduction may be made temporarily during a time of light load. In general, a system design that gives permanently large lagging kv-a. requirements is not the most economical.

## VI. METHODS OF STARTING SYNCHRONOUS CONDENSERS

It is standard practise to provide synchronous condensers with amortisseur windings and to start them from a low-voltage transformer tap or from an autotransformer. This method of starting is readily adaptable to automatic operation, and the equipment required costs less than a starting motor with its control and the necessary synchronizing apparatus. Unless a source of low voltage for the starting motor is already available, an extra transformer must be provided for it, and in this case the cost is very much greater; also, automatic operation with a starting motor is more difficult. The only apparent advantage of a starting motor is the possibility of securing a lower reactive component of the initial starting current by its means.

As the starting kv-a. required by a standard condenser is only about 30 per cent of normal, and this can be reduced to about 20 per cent by adding oil pressure starting equipment, it does not seem that the use of a starting motor is ever necessary on this account. However, in rare cases it may be desirable occasionally to use a condenser for line charging or for testing a transmission line, and a starting motor will then be necessary. If a condenser is to be operated on unbalanced voltages or under other conditions where a very low-resistance amortisseur winding is needed, the condenser's starting characteristics will be poor and a starting motor will be desirable.

In order to keep down the induced field voltage, it is customary to short circuit the field through a resistor during the starting period. The condenser will then come up to full speed on the tap voltage, and field is applied before it is thrown over to full voltage. When the change to full voltage is made, the field current being kept constant, the kv-a. drawn from the line will change suddenly by an amount depending on the value of field current used. Let $T$ represent the ratio of tap to line voltage, $Y_s$ the ratio of lagging to leading kv-a. capacity, and $E$ the ratio of the field current during synchronizing to the no-load field current. Then the leading kv-a., drawn from the line on the tap, are represented by:

$$T\,(E - T)\,Y_s$$

and the leading kv-a. on full voltage are:

$$(E - 1)\,Y_s$$

For minimum shock to the system, these two must be equal, whence we find the best value of field current to use on synchronizing is:

$$E = T + 1 \tag{5}$$

which gives leading kv-a. equal to $T\,Y_s$.

As a standard condenser usually has a no-load field current equal to about one-third of its full-load field current, and as the tap voltage used for starting is usually not over 30 per cent, equation (**5**) shows that the best value of field current for synchronizing is a little less than 40 per cent of its rated value.

In practise it is convenient for the operator to determine the best value of field current by taking two *V* curves on the condenser, one at full voltage and one on the starting tap, reading the current input on the line side of the compensator. Then, as indicated in Fig. 5, it is a simple matter to prolong the leading branches of the two *V* curves until they intersect, and this will give the desired field current. The magnetizing kv-a. of the compensator are usually large enough to make the determination by readings on the low side of the compensator considerably in error, as indicated by the dotted line in Fig. 5.

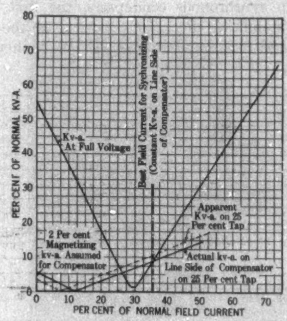

FIG. 5—VOLTAGE CURVES OF A 7500-KV-A. SYNCHRONOUS CONDENSER

Showing method of determining best field current for synchronizing

Previous articles dealing with this question have sometimes recommended the field current value corresponding to the same armature current on the leading branch of the low-voltage *V* curve and on the lagging branch of the full-voltage curve. In this case, the change from leading to lagging kv-a. will give an appreciable shock to the system, as the system excitation must change immediately in the opposite direction. As there is practically no torque exerted by the condenser, the phase position of the pole with respect to the armature current is nearly the same for all values of excitation, and, therefore, whatever value of field current is used, there should be very little shock to the condenser itself.

Since the transition from the tap to full voltage can be made without requiring any appreciable change in the phase position of the rotor or in the total kv-a. drawn from the line, it is not of great importance whether the circuit is momentarily opened during the transfer or not. If the circuit is held open for an unnecessarily long time, amounting to a second or more, the rotor will fall back in phase and a mechanical shock will be experienced on reclosing.

Instead of first closing the field through a resistor and later opening the resistor circuit and applying field voltage, it is often convenient to simply close the field through the direct connected exciter at the beginning, and allow the machine to synchronize itself on the tap voltage. In this case, the exciter must build up so slowly that the direct component of the field current does not become important until the condenser is at speed. If the exciter builds up too rapidly, the machine will not come up to full speed. The remedies in such a case are either to cut in more resistance in the exciter field circuit, or to use a higher tap voltage for starting.

## VII. STABILITY OF SYNCHRONOUS CONDENSERS

There are two aspects of the stability question as it relates to synchronous condensers, the first dealing with the stabilizing effect of a condenser on the system voltage, and the second dealing with the ability of the condenser to stay in synchronism during system disturbances. These will be considered in turn.

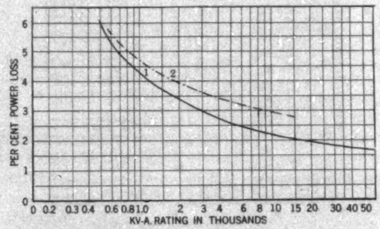

FIG. 6—POWER LOSSES OF SYNCHRONOUS CONDENSERS

**Corresponding to usual manufactures guarantees**

A dead system load, made up of lamps, resistors, reactors and so forth, is characterized by a constant ratio between its voltage and current. If the voltage rises or falls, the current does likewise in an equal ratio, without change of power factor. A live load, made up of synchronous and induction motors, is characterized by a constant kilowatt demand, independent of voltage, so that in this case the power component of current rises if the voltage falls, and vice versa. With a dead load, therefore, a fall in voltage results in a decrease in line drop, while with a live load a fall in voltage gives an increased line drop. The former is always a stable, and the latter may be an unstable condition.

For good system stability, it is necessary to counteract the effects of a live load by adding equipment that will give a rapid decrease in the line drop whenever the voltage falls. A static condenser is of no use for this purpose, as the current falls with the voltage, and thus the voltage rise it produces falls also, increasing the instability. An induction voltage regulator can be used, but its effect is secured by the action of its control mechanism, and so is not immediate. On the other hand, a synchronous condenser fulfils the desired conditions, as it gives an increased leading current when the voltage falls, and vice versa. The action in this case is immediate, as the field excitation is always equal to the sum of the values required to produce the voltage and the armature current, and any decrease in one results in an equivalent increase in the other. This property of the synchronous condenser is of the greatest importance in problems of system stability.

By automatic voltage regulator control of the condenser field current, a delayed action of the same kind, that further increases the leading current when the voltage falls, can be secured, and, by using a quick-response excitation system with a proper voltage regulator, the time delay in securing the additional effect can be made very short. Or, by designing the condenser with a strongly saturated magnetic circuit at normal voltage, a large amount of field excitation will be released by a fall in voltage, and made available for the production of additional leading armature current. As Fig. 3 indicates, a normal condenser gives a slight increase in total leading kv-a. as the voltage falls, while a saturated machine gives a large increase. Thus, by the use of a saturated design the armature current may be made to instantaneously increase much more rapidly than the voltage decreases, even with a fixed field current. It is probable that these two ideas of a quick response excitation system and a saturated magnetic circuit will prove to be very useful in solving the future stability problems of large systems.

A standard synchronous condenser with about 50 per cent lagging kv-a. capacity has a pull-out torque of about 175 per cent of its rated kv-a., with full excitation. At no-load, the pull-out torque is reduced to about 75 per cent, and even with zero field current, corresponding to full lagging kv-a., it still has a pull-out torque of about 20 per cent of its rating. A condenser designed for 100 per cent lagging capacity has corresponding pull-out torque values of about 225, 125, and 30 per cent. A standard condenser of 5000 kv-a., or above, also has a value of $W R^2$ equal to:

$$W R^2 = (6 \text{ to } 8)\ (\text{kv-a.}) \left( \frac{1000}{\text{rev. per. min.}} \right)^2 \text{lb. ft. squared} \qquad (6)$$

The familiar equation for the torque required to produce angular acceleration in a rotating mass can now be applied to determine what rate of change of frequency can occur without the condenser falling out of synchronism. This equation is:

$$\frac{W R^2}{g} \ \frac{d w}{d t} = \text{torque}, \qquad (7)$$

where the moment of inertia in pound-feet-seconds squared is:

$$\frac{W R^2}{g} = \left(\frac{7}{32.2}\right) (\text{kv-a.}) \left(\frac{1000}{\text{rev. per. min.}}\right)^2, \quad \text{approximately,} \qquad (8)$$

the angular acceleration in radians per sec. squared is:

$$\frac{d w}{d t} = w \left(\frac{d w}{w d t}\right) = w \frac{d f}{f d t}$$

$$= \left(\frac{2 \pi}{60}\right) (\text{rev. per. min.}) \frac{d f}{f d t}, \qquad (9)$$

and the torque in foot-pounds is:

$$\text{Torque} = (0.2 \text{ to } 1.75) \frac{7040 \text{ (kv-a.)}}{\text{rev. per. min.}} \qquad (10)$$

Substituting these expressions in (7), we find the allowable rate of change of frequency for a standard condenser to be:

$$\frac{d f}{f d t} = 0.06 \text{ for zero field excitation}$$

$$= 0.23 \text{ for no-load excitation}$$

$$= 0.55 \text{ for full-load excitation} \qquad (11)$$

This means that the frequency could be changed 55 per cent per sec. without causing a standard condenser operating at rated field excitation to fall out of step, *provided the voltages at its terminals were held absolutely constant and balanced.* In practise, a system disturbance usually both lowers and unbalances the voltage, so the actually allowable rate of frequency change is much less.

The torque developed varies as the square of the voltage with no field excitation (full lagging operation), and just a little faster than the first power of the voltage at normal excitation (full leading operation). If one line terminal is opened, the condenser operates single-phase, and has a pull-out torque about 70 per cent of its value at the same voltage three-phase. If, however, the voltage between two terminals falls very far, corresponding to a short circuit between lines, the short-circuited phase acts as a generator feeding power to the fault, and the pull-out torque is reduced still more. Also, the existence of reactance in the lines and transformers may greatly reduce the pull-out torque. On the whole, therefore, taking into account these factors and remembering that the maximum torque of a synchronous machine is not fully available, due to the hunting that always occurs on disturbances, it is probable that not more than 10 per cent of the rate of frequency change given by (11) is permissible.

Our conclusion is that a condenser operating at rated field current will stay in step during system disturbances if the frequency does not change more rapidly than 5 per cent per sec.; and at zero field current it will stay in step during frequency changes up to ½ per cent per sec. If it falls out of step when the field excitation is very small, the condenser will behave like an induction motor and will come right back into step after the disturbance is over, while at large excitations, it will come to rest and must be restarted; hence, the lessened stability of a condenser at reduced excitations is not of particular importance. On the basis of these figures, it seems that standard condensers have ample synchronizing power for ordinary applications and that no weight need be attached to this factor in writing condenser specifications.

## VIII. RECENT IMPROVEMENTS IN CONDENSER DESIGN

Designers are always striving to make more efficient, cooler, and more reliable machines without increasing the cost, and the results of their efforts should be recorded at intervals. There are several recent improvements in condenser design that seem worth presentation here.

The design of amortisseur windings, especially the end rings, has always presented a serious problem on large high-speed machines, as the support of the projecting bars and rings has proved mechanically difficult. Furthermore, the presence of a complete end ring has been very inconvenient in taking down and reassembling the poles. By simply omitting any end-ring connection between poles, the amortisseur winding bars can be shortened, and the ring segment placed close to the pole piece punchings. The expansion of the bars due to heating during starting is taken care of by leaving a small axial clearance between the rings and the pole pieces. This gives a very happy solution to the problem, as it avoids all mechanical difficulties and dangers from overheating of the exposed bars, and greatly facilitates assembly. Most advances in the art bring complications in their train, and it is therefore extremely pleasant to be able to record one that simplifies the design instead. Fig. 7 illustrates this construction.

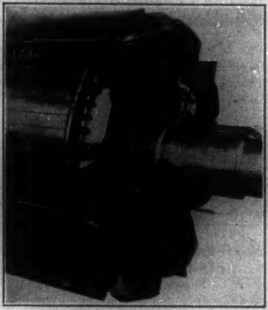

FIG. 7—ROTOR OF 7500-KV-A., 900-REV. PER MIN. SYNCHRONOUS CONDENSER

Showing open amortisseur winding and finned field coils

Fig. 7 shows the rotor of the same 7500 kv-a., 900 rev. per. min. synchronous condenser referred to in the previous discussions, on which this simplified amortisseur winding construction was used. The deterrent to the use of this scheme heretofore has been the thought that it would give unsatisfactory starting characteristics. The machine shown, and many others of different sizes, have been built in this way, however, without any important difficulties from this source being experienced.

Another recent improvement in rotor design consists of the addition of fins to the ends of the field winding, as illustrated in Fig. 7. These fins are made by simply projecting every second or third turn of the field coil during winding. They give an increased area for cooling on the ends, where it is most effective, and so reduce the field temperature.

In the design of the stator, improvements have taken the form of simpler and stronger mechanical construction by the use of steel plates welded together instead of castings, and in improved arrangements for ventilation. Fig. 8 shows a 10-pole, 20,000-kv-a., 720-rev. per. min., 11,000-volt, synchronous condenser recently built.

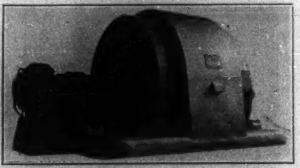

FIG. 8—20,000-KV-A., 720-REV. PER MIN., 11,000-VOLT SYNCHRONOUS CONDENSER
**Showing steel plate frame**

The welded frame is much lighter than an equivalent casting, and is more easily modified to meet special requirements.

A strong tendency to the use of closed systems of ventilation for large rotating machines, including condensers, has been recently observed. The addition of the necessary enclosing features and water coolers adds about 10 per cent to the first cost of the condenser itself, but it reduces noise to a very small amount, and it is found to give much longer insulation life. The number of cubic feet of ventilating air passing through an open machine is so great that astonishing amounts of dirt can collect on the windings in a short time. For every kilowatt of loss, a machine requires about 100 cu. ft. of cooling air per min., or, on the basis of 8000 hrs. of operation annually, about 50,000,000 cu. ft. each year.

The air found in ordinary buildings usually contains between 0.02 and 0.2 lb. of dust per 1,000,000 cu. ft.,[6] and we may take 0.03 as representing reasonably good conditions. If 10 per cent of the dust in the ventilating air is deposited as it passes through the machine, then 0.15 lb. are deposited annually for each kilowatt of loss. Most large condensers have sufficient cooling air to provide for losses equal to 3 per cent of the rating, so that this means about 4½ lb. dirt per 1000 kv-a. of rating. On a 50,000-kv-a. condenser, this gives a total of over 200 lb. of dirt deposited annually.

The presence of dirt on the windings and in the air ducts increases, of course, both the temperature rise and the fire risk, so that the use of a closed system of ventilation prevents deterioration of the insulation and provides valuable insurance. These advantages sufficiently explain why the 50,000-kv-a. condensers recently built have been provided with closed system ventilation and water coolers. There is no doubt that an increasing percentage of large machines will be built in this way in the future.

Last, but not least, steady reductions in the losses of synchronous condensers have been going on. In Fig. 6, the usually guaranteed losses of standard condensers of voltages and speeds as given in Table I are shown in comparison with those existing four years ago. Of course, considerable variations from the curve values occur due to the special conditions in each case; nevertheless, the curve can be relied upon for preliminary calculations of the cost of condenser losses in projected installations.

These reduced losses have been obtained by using better proportions in design, so that there is a good balance between the several items of loss, by using better grades of steel, and by employing effective winding transpositions to avoid eddy-current losses. As these features result in more expensive machines than necessary from an operating viewpoint alone, it is important that specifications for individual machines give the value that is to be assigned to savings in losses.

## IX. ASYNCHRONOUS CONDENSERS

It is possible to secure a very flexible and stable machine that will give a wide range of leading or lagging kv-a. by exciting a slipring induction machine from a direct connected a-c. exciter. Such a machine will operate at a very small slip that varies with the losses, the sum of the speed and excitation frequencies beings always equal to the line frequency. Hence, it has extremely good stability and will not fall out of step on system disturbances. With excitation in one direction, it gives leading kv-a., and with reversed excitation it gives lagging kv-a., the limits in both directions being set by exciter capacity and heating.

While this type of machine has found fairly extensive use abroad, it does not seem desirable for use in the United States, for, the rotor winding must be distributed in many slots, thus greatly reducing its current carrying capacity, and so the size and cost for leading power-factor operation are much in excess of those of a corresponding synchronous condenser. Also, in order to partially overcome this handicap, it must have a small air-gap, and a large number of stator slots, which increase both losses and cost.

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[6] Margaret Ingels, "How Dusty is Air," *Jl. Am. Soc. of Heating and Ventilating Engineers*, Vol. 31, pp. 415-418, Aug., 1925.

Its two advantages of extra stability and extra lagging kv-a. capacity are not important here. As pointed out in section VII, the usual standard condensers appear to have ample stability for ordinary applications. This can be attributed to the short time settings of the protective relays generally used in this country, which cut off faults before other machines are noticeably affected. Without protective relays, or with time settings of five sec. or more, the stability of synchronous condensers may become a limiting feature. As indicated above, the costs of synchronous machines with lagging capacities up to 100 per cent of the rating are much less than those of equivalent asynchronous machines.

Finally, the important advantage of synchronous condensers in stabilizing the voltage, discussed in section VII, is lost with the simplest form of asynchronous condenser, which has its a-c. exciter fed from a transformer connected to the main lines. For, in such a machine, the exciting current decreases proportionally to the line voltage, and so the leading current decreases also, making the apparatus equivalent to a static condenser only. This defect can be overcome by providing an auxiliary motor-driven synchronous generator to feed the exciter, at some extra expense, when the machine becomes equivalent to an unsaturated synchronous condenser.

## X. CONCLUSIONS

From this discussion, several fairly definite conclusions can be drawn. These may be listed as follows:

1. The most economical speeds and voltages for synchronous condensers are approximately those listed in Table I. If quiet operation is important, it should be secured by enclosing features rather than by resorting to lower speeds.

2. Standard synchronous condensers have ratios of lagging to leading kv-a. capacity of approximately 0.5. To require a ratio of unity means an increase in size of about 25 per cent above standard, together with a slight sacrifice in efficiency.

3. To obtain greater lagging kv-a. capacity reconnection, or variable voltage operation of synchronous condensers is not generally desirable, but may be justified in special cases.

4. The use of reactors to supplement the lagging kv-a. capacity of standard synchronous condensers offers many advantages, and may be generally preferable to the use of special condensers with large lagging capacities.

5. The standard method of starting synchronous condensers as induction machines on reduced voltage is preferable to the use of a starting motor. If especially low starting kv-a. are desired, oil pressure starting equipment should be provided.

6. The least disturbance on synchronizing will take place when the field current at changeover from the tap to full voltage is made equal to $(T + 1)$ times the no-load field current, or roughly, 40 per cent of the rated field current of a standard condenser.

7. By the use of a saturated magnetic circuit or a quick response excitation system, the already great voltage stabilizing influence of a synchronous condenser can be considerably increased.

8. Present standard condensers have adequate synchronizing power, and should stay in step on system disturbances in which the frequency does not change faster than 5 per cent per sec. at rated excitation, or one-half per cent per sec. at zero excitation.

9. The use of asynchronous condensers presents no important advantages over the usual synchronous condensers, and is accompanied by a sacrifice in cost and losses.

The author wishes to express his appreciation of the assistance given him by Messrs. L. W. Riggs and O. A. Gustafson in the preparation of this paper.

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## Discussion

**R. H. Park:** Usually, synchronous condensers are purchased for power factor correction and voltage regulation. It is sometimes desirable, however, to purchase additional condenser capacity in order to secure greater stability either in steady operation, or during transient periods of instability, such as are occasioned by short circuits and sudden load changes.

The ability of a condenser to improve stability under steady conditions depends upon the values of its synchronous and transient reactances, although the relative importance of these two has not yet been convincingly established. It also depends upon the type of voltage regulator employed and on the speed of response of its exciter.

On the other hand, the ability of a condenser to improve stability during system transients occasioned by short circuits is determined largely by the amount of leading current which the condenser can supply to the system, and thus by the transient reactance and the speed with which the excitation system can vary the condenser field voltage over a wide range. If insufficient range of exciter voltage is available, the advantage derived by effecting the available voltage change quickly will be slight.

Thus, where stability considerations are important, it may be desirable to provide an exciter of considerably greater voltage range than for normal application. Also, it may be desirable to use special condensers designed for low transient reactance. I should like to ask Mr. Alger, therefore, which is economically more desirable, to secure low transient reactance by a special design of condenser, or by using a standard condenser of larger size.

**M. W. Smith:** Mr. Alger has brought out some interesting and practical considerations in the design and operation of synchronous condensers. A timely plea has also been made for standardization of requirements and characteristics which affect design proportions. Standardization is, of course, desirable in all classes of apparatus, but for obvious reasons, synchronous condensers probably offer more possibilities in this respect than any other large rotating apparatus. Considerable movement in this direction can be made without impairing the quality of the apparatus, and which will result in benefits to both the operating companies and the manufacturers.

Past experience has usually shown that the variable having most effect on synchronous-condenser design proportions, is the ratio of lagging to leading kv-a. capacity. Mr. Alger has proposed several methods for obtaining increased lagging kv-a. capacity from machines of standard proportions. All of these methods may be applied in special cases, but the use of suitable reactors is about the only method proposed that can be offered as a general application. It seems doubtful if even this method can be applied economically in most cases. It has been noted that where large percentages of lagging kv-a. capacity are specified, machines of special and abnormal proportions have usually been supplied after all conditions were considered. This results in units which are comparatively expensive and inefficient. Every effort should, therefore, be made to keep the requirement for lagging capacity down as close to 50 per cent of the leading kv-a. capacity as possible. This consideration should be kept in mind in the operation and layout of power system as far as economic considerations will permit.

**P. L. Alger:** Answering Mr. Park's inquiry, I believe that the most economical way to secure abnormally low transient reactance in a synchronous condenser is to use an oversized machine with a standard field, but a special armature. The per cent reactance is nearly the same for all standard machines, so that by merely using the next larger standard rating, a proportional decrease in reactance is secured. However, this larger machine will have more armature copper and larger slots, than are necessary for the new rating, and so a further reduction in the per cent transient reactance can be secured by using a special armature winding with shallower slots. The saving in cost of copper and insulation here will more than offset the cost of the special features. By these means, the transient reactance can be reduced about 10 per cent faster than the corresponding standard rating is increased. By using field poles, shorter and narrower than standard, additional gains could be made, but at greater expense, and with a greater loss of efficiency.

# Oscillograph Recording Apparatus

## For Transmission Line Studies

BY JOSEPH W. LEGG[1]

Associate, A. I. E. E.

***Synopsis.**—Part I is an introduction, showing the need for reliable records of power disturbances in transmission lines, and showing that the incandescent-lamp oscillograph is the only practicable recorder of such chance disturbances.*

*Part II describes the Power Osiso which is a very compact and highly efficient oscillograph, having an instantaneous wattmeter, a permanent-magnet galvanometer, and a relay arrangement with control for automatic operation on chance disturbances. The various auxiliary apparatus, such as daylight-loading film holders, 6-volt motor, potential circuit control, etc., is also described, together with different connections for the same.*

*Part III describes the Multi-Element Oscillograph, which gives from 3 to 9 simultaneous records on one film, also the various auxiliary apparatus and the possible combinations thereof. A detailed description is given of the automatic operation equipment and its action in recording chance disturbances.*

### PART I. INTRODUCTION

IN this day of complex power circuits it is very desirable to have reliable records of system behavior during disturbances. A most satisfactory recorder of such disturbances is an oscillograph using an incandescent lamp, because such an instrument can be easily arranged to function automatically and to give sufficiently high-speed records.

Automatic operation of standard oscillographs on chance disturbances[2] has been advocated for nearly a decade, but has not been utilized by operating engineers until recently. The present stage of development of such apparatus has advanced to such an extent that it is even possible to obtain records within the first half cycle of power flow following a lightning stroke or other chance disturbances. Thus this apparatus is much quicker in action than is absolutely necessary for stability studies and will even show the rupturing characteristics of lightning arresters and high-speed circuit breakers.

It was hoped that graphic-chart instruments could be made fast enough to catch the surges in power which affect the stability of a system. However when charts were compared with oscillograms, taken simultaneously, it was seen that the highest-speed graphic instruments are hopelessly slow in following rapid fluctuations in power. An instantaneous oscillographic wattmeter was calculated some time ago, but its complete development was delayed because of the hope that a practicable graphic instrument could be made fast enough for stability investigations. When it was found that a reconstructed high-speed graphic instrument, with over fifty times normal input, would not tell as complete a story as the oscillographic wattmeter, then it was conceded that the oscillograph is the only practicable instrument for recording power disturbances. Furthermore, the reconstructed high-speed graphic required an elaborate installation of extra potential and current transformers, besides multi-contact relays to cut out the instrument before it could be destroyed by fifty-times normal input. On the other hand, the oscillographic wattmeter takes less energy than standard graphic instruments.

This paper is to describe improved forms of oscillographs applicable to power circuit analysis, and to indicate the types of elements new or old, required for recording the electrical quantities involved, and their proper arrangement in the various circuits. The outfits discussed are in two different forms. The smaller outfit is known as the Power Osiso and gives one or two simultaneous records, of instantaneous power or potential or current, on one film $3\frac{5}{8}$ in. wide. The larger outfit is known as the Multi-Element Oscillograph, see Fig. 1, and gives from three to nine simultaneous records on one film 7 in. wide. Each outfit may be equipped with instantaneous wattmeter elements and with a suitable relay arrangement for automatic operation on chance disturbances.

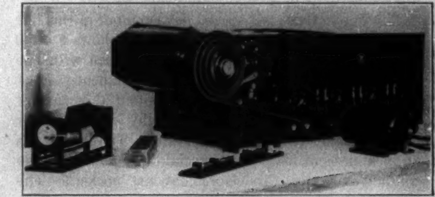

FIG. 1—COMPLETE MULTI-ELEMENT OSCILLOGRAPH WITH DRIVING-MOTOR ATTACHED TO FILM HOLDER, VIEWING MIRRORS RESTING AT ONE SIDE

### PART II. THE POWER OSISO

There are several forms of the Osiso,[3] but only the newest form, developed especially for power investigations, will be described in detail in this paper. Each Osiso is a very portable and highly efficient oscillograph

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[1] Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

[2] See TRANS. A. I. E. E. Vol. XLII, 1923, p. 385 section on Automatic Operation, in article entitled *Expansion of Oscillography by the Portable Instrument*, by the author.

*Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., Sept. 13-16, 1927.*

[3] See *The Electric Journal* for December 1924 and July 1927.

which gives more clean cut photographic records with a two-watt lamp than we have been able to obtain with any other oscillograph even though the latter uses a direct-current arc lamp. The Osiso is 6¼ in. wide, 9 in. high, and 10 in. long, including all parts except the photographic film holder and its driving motor. Fig. 2 shows the original form of the Osiso with a daylight-loading film holder and a six-volt shunt motor attached. The micarta case contains the incandescent lamp illuminant; resistors for the potential circuits, up to 250 volts; one or two galvanometer elements; complete optical system; and convenient binding posts for all connections. There are side openings which can be fitted with detachable panels equipped according to the particular application desired.

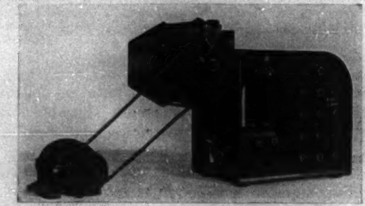


FIG. 2—STANDARD OSISO WITH DAYLIGHT-LOADING FILM HOLDER AND DRIVING MOTOR ATTACHED

The Power Osiso is a special development in this line for power-circuit investigations. Fig. 3 shows a cross sectional view of the Power Osiso equipped with one instantaneous wattmeter and one permanent-magnet galvanometer, for recording either potential or current waves. The Osiso lamp was especially developed for this extremely portable oscillograph. The lamp has an incandescent filament, a special bulb, and a double-contact vase for candelabra bayonet sockets. The filament is kept straight by a spring support. Two capacities are furnished, one for approximately one-half ampere, and the other for approximately two amperes, both at 4 volts.

The one-half ampere lamp has the characteristic of lighting quickly when connected across a constant potential supply with no series resistance, and going out quickly when disconnected from the supply. This makes it possible to take a single photographic exposure, on a fast rotating film, by exciting the lamp for one revolution of the film drum. This lamp gives sufficient light, on short-time abnormal voltages, to take fairly high-speed oscillograms (10 in. in 0.05 second).

The two-ampere lamp gives splendid illumination for viewing audio-frequency waves, so that several people may see the waves at the same time. Moderate-speed oscillograms may be taken for quite a period of time, with normal, or slightly abnormal, voltage on this lamp.

Undesirable reflections from the rear, inside, surface of the globe have been prevented by a special construction of the glass bulb.

The vertical filament of the lamp shines on the tiny mirrors of the two vertical vibrators of standard design. Beams of light are reflected from there to two reflecting prisms which in turn reflect each beam of light upwards to a long horizontal reflecting prism and from thence, horizontally, to the front of the instrument. Here the narrow ribbon-like beams pass through the cylindrical lens and are condensed to two separate points on the photographic film. In the permanent magnet galvanometer the vibrator mirror deflects in proportion to the instantaneous value of current passing through the vibrator strips.

### INSTANTANEOUS WATTMETER

The vibrator element of the instantaneous wattmeter is the same as that which has been used with electro-magnet and permanent-magnet galvanometers for many years. As is usual with oscillographs the vibrators are surrounded by a transparent oil for critically damping the movements. The electro-magnet is very much smaller and lighter in weight than that of any other oscillograph. The complete galvanometers are but 3¼ in. high, overall, above the base of the Osiso. The laminated hypernick steel core of the wattmeter magnet and its copper winding respond to instantaneous values of alternating currents. Fig. 4 shows the instantaneous watt-galvanometer disassembled. Normal magnetic strength is obtained with a drop of only 1½ volt at 5 amperes, with 60 cycles current. With this magnet excitation the vibrator consumes but 0.03 amperes, r. m. s., from the potential circuit to give one inch extreme deflection on the photographic film. The total energy consumption is less than one per cent of that taken by the reconstructed high-speed graphic instruments whose response was more than 100 times slower.

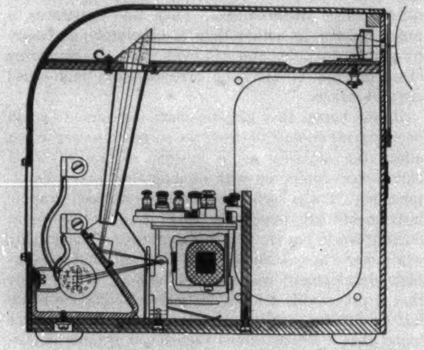


FIG. 3—CROSS SECTIONAL VIEW OF THE POWER OSISO

Even though the Osiso is a small fraction of the size and weight of an arc-lamp oscillograph, it is just as sensitive and considerably more efficient. Furthermore the Osiso will do many things which cannot be done with any predecessor. When in a single-phase system this instrument shows true instantaneous power. The instantaneous watt record enables one to scale off values of kv-a., power-factor, and average power. Fig. 5 shows how these values may be taken from the curve, assuming that the records are sine waves. The single-phase watt galvanometer may be connected in three-phase lines by means of a three-circuit resistor or twin-transformer arrangement, either of which may be supplied within the Osiso proper. In most power-system disturbances, the ground current becomes zero, or negligible, by the time the surges of actual power are important. Those cases in which the disturbances are most severe, the system approaching instability, the power continues to oscillate some time after the relief of short circuit. Hence the single-phase wattmeter, properly connected, shows the important power surges, and also shows the variations in kv-a. and power factor. A polyphase instantaneous wattmeter (described later) has been designed to go in the same space as the single-phase or the permanent-magnet units. However, the less expensive and more accurate single-phase unit tells a greater story than the polyphase unit, since the latter will not show kv-a. and power factor.

FIG. 4—THE INSTANTANEOUS WATT GALVANOMETER DISASSEMBLED

All these vibrator elements give a deflection proportional to the current, potential, or power which they are recording. The deflections are not proportional to the square of the current, as is the case in a-c. indicators, but to the first power of the current as in a D'Arsonval instrument. The galvanometers are true oscillograph galvanometers and not compromises or improvised indicators. In the few cases where it is desired to give a deflection in proportion to the heating effect of the current, this may be done by placing the single-phase wattmeter vibrator across a 5-ampere shunt which is in series with the 5-ampere current coil of the wattmeter.

### GALVANOMETER CONNECTIONS

This paper does not attempt to show all the various ways in which the oscillograph galvanometers may be connected in the instrument transformer circuits of transmission lines. Reference may be made to the contemporary paper by Messrs. J. C. Wood, Lloyd F. Hunt, and S. C. Griscom entitled *Transients due to Short Circuits* and to Mr. Roy Wilkin's paper on *Practical Aspects of System Stability*, A. I. E. E. TRANSACTIONS of 1926, and to an article by R. D. Evans entitled "New Sequence System of Polyphase Meters" in the *Electrical World*, February 10, 1923.

In stability analyses one is interested in power measurement largely because of its effect upon acceleration or deceleration of the rotors of generators. The low sides of transformers to which generators are connected are usually in delta, so that in this circuit there can only be positive and negative sequence power. The negative sequence power is usually small or can be corrected for, or calculated, so that the important quantity is positive sequence power. This can be obtained readily by the sequence connections.

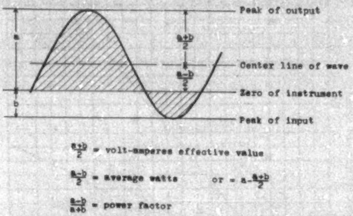

Peak of output
a
$\frac{a+b}{2}$
Center line of wave
$\frac{a-b}{2}$
Zero of instrument
b
Peak of input
$\frac{a+b}{2}$ = volt-amperes effective value
$\frac{a-b}{2}$ = average watts or = $a-\frac{a+b}{2}$
$\frac{a-b}{a+b}$ = power factor

FIG. 5—INSTANTANEOUS WATT DIAGRAM

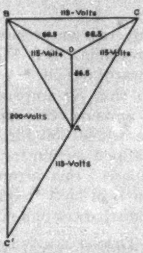


FIG. 6—DIAGRAM OF ARTIFICIAL NEUTRAL, AND POTENTIAL TRANSFORMER VOLTAGES

Various forms of phase-sequence networks may be used for certain tests, but for most purposes where only two simultaneous records are to be taken it will be found best to use the single-phase instantaneous watt-meter connected to show three-phase power, kilovolt-amperes, and power factor. The permanent-magnet galvanometer may then be used to record any one line current, or any line potential from the neutral to any line. Standard potential and current transformers, used for other instruments, will supply the necessary power for the oscillograph galvanometers without affecting the reading of the other instruments.

### THREE-CIRCUIT RESISTORS

The three-circuit resistor consists of six units of 1000 ohms each, making two units per set. When these sets are *Y* connected to form an artificial neutral to a three-phase 115 volt circuit (Fig. 6) the instantaneous wattmeter vibrator is placed in series with any one of these sets and the current coil is placed in the 5-ampere secondary of the current transformer pertaining to the line of that set. This arrangement gives ample variation in deflection for all currents from 1.5 amperes to approximately 8 amperes, where saturation of the iron begins to be appreciable. See Fig. 7, taken with 0.033 ampere in vibrator circuit. A tap is provided on the current coil so that 30 amperes gives the same flux density as 5 amperes through the whole coil. Thus by using the whole coil for currents up to 8 amperes, and the tapped section for overload currents from 6 to 40 amperes, this arrangement covers a broader range than is usually required for studying staged or chance disturbances in a-c. power systems.

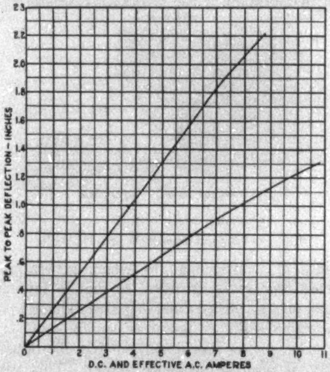


FIG. 7—TYPICAL CALIBRATION CURVE OF INSTANTANEOUS WATTMETER, WITH 0.033 AMPERE IN VIBRATOR

### TWIN-TRANSFORMER PANEL

A panel is available carrying two small potential transformers and two rheostats so arranged as to fit in the side openings of the Power Osiso. The transformers are wound for 120 to 1.2 volts, and furnish a convenient means of replacing resistances in making the necessary phase-changing connections in the application of the single-phase wattmeter to the three-phase circuit. In the use of the polyphase-wattmeter element described below, the transformers are necessary because of the interconnection of the different phase circuits in the wattmeter.

### POLYPHASE WATTMETER

The vibrating part of the polyphase wattmeter is exactly the same as that of the ordinary sensitive vibrator except that the two vibrator strips are connected together at their center, under the tiny mirror, by a short length of the same material. This construction is just as strong as for the single-phase vibrator and permits the vibrator strips to be under the usual tension of approximately 50,000 lb. per sq. in. The ivory bridges, on the vibrator frame of this polyphase unit, are the same distance apart (one inch) as in the single-phase unit. The two upper extremities of the vibrator strips are connected to the usual binding posts. In this case there are two lower extremities (instead of the usual loop) and these are connected to levers and thence to insulated leads which pass to two other binding posts on the element top. The levers are insulated from the frame, and from each other, and are connected, by an equalizer, to the usual tension spring.

In this polyphase galvanometer there are two separate field windings, on separate, inclined, laminated iron cores. The active air gaps in all magnets are 0.032 in. or less, and it is in this space that the vibrators act without touching the pole faces of the magnets.

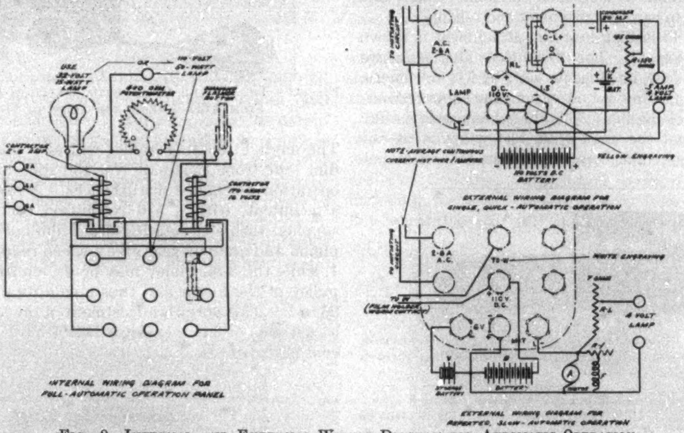
This polyphase oscillographic wattmeter will not show kv-a. nor power factor, but is better than the single-phase instrument for showing true power during transients in a delta-connected circuit. It is, of course, not applicable at the instant current flows through the fourth wire (ground) in a star connected circuit.

### AUTOMATIC OPERATION PANEL

A full-automatic operation panel is designed to occupy the opening in either side of the Osiso. This panel is shown in Fig. 8, with internal and external wiring in Fig. 9. The panel has an initiating relay, to operate from the secondary of a current transformer, preferably in the ground-to-neutral circuit of the power system. The closing of this relay starts the Osiso to function on a chance disturbance. A second relay acts to hold the lamp and motor circuit closed. A thermostatic cut-out may be set to drop out the second relay after the desired period of time has elapsed, usually between 3 and 15 sec. A rheostat or potentiometer is supplied on the panel to control the time of heating the thermostatic cutout. A socket is included

FIG. 8—AUTOMATIC OPERATION PANEL FOR THE OSISO

for a protective lamp which also acts as a signal. This automatic-operation panel may be connected in several different ways according to the type of automatic operation desired. One connection is for single, quick-automatic operation. This throws the 4-volt, ½ ampere Osiso lamp across a 20-microfarad condenser, charged to 110 volts direct current, when the initiating relay closes. This is shown in the upper right-hand diagram of Fig. 9. The photographic film must be kept rotating continuously for such high-speed operation. The thermostatic cutout is set to open the second relay by the time the film drum has made one revolution. A fuse blows when both relays are closed so that the apparatus will not operate again until the film is changed by the station attendant.



INTERNAL WIRING DIAGRAM FOR FULL-AUTOMATIC OPERATION PANEL

EXTERNAL WIRING DIAGRAM FOR SINGLE, QUICK-AUTOMATIC OPERATION

EXTERNAL WIRING DIAGRAM FOR REPEATED, SLOW-AUTOMATIC OPERATION

Fig. 9—Internal and External Wiring Diagram for Automatic Operation

### Quick Action

Since the lamp comes up to full brilliancy in less than a thousandth of a second after the closing of the first relay, and since this relay will operate in a fraction of a cycle under a great sudden overload, and since the film is rotating continuously, a perfect oscillographic record is started several cycles before the oil circuit breaker can function. If the chance disturbances clear themselves before the first or succeeding operation of the breaker the record will show this fact. If a power surge follows the circuit breaker action, the record shows that also. For such operation the film holder must be supplied with a strip film which must pass entirely around the drum, so that all of the record will be there irrespective of the position of the drum at the instant of the lighting of the lamp. With a high-speed direct-current relay, operating on the steepness of wave front principle, it is possible to start exposures within two thousandths of a second after the start of a short circuit on a direct-current power system.

### Repeated Action

Repeated automatic operation may be obtained by connecting the panel according to the lower right-hand diagram in Fig. 9. In this case the records do not start as quickly, since the film must be brought up to speed by the driving motor and the lamp is merely thrown across six volts of the storage battery. In this case the film travels forward a few inches each operation and requires no attention until many automatic operations have taken place, each recording a different disturbance. If it is desired, a 10-in. or a 5-ft. film may be driven entirely through on the first operation, but usually several records will be taken on each 5-ft. film. In any case the photographic film can be brought up to sufficient speed to give a good record of the action of large oil circuit breakers. The film speed will be fairly uniform during the power surges which may follow the breaker action.

### Driving Motors

Fig. 10 shows the Power Osiso with the automatic-operation panel and 6-volt shunt-motor unit. The driving motor unit is arranged with a field rheostat and a double-pole switch so that the armature may be supplied with 2, 4, or 6 volts to give a considerable range of speed to the photographic film. A 110-volt series-motor unit is available with a rheostat across the armature brushes. This is satisfactory for continuous rotation of the film drum but not for quick pick up of speed on repeated automatic operation. The shunt motor brings the film up to constant speed in a much shorter line.

### TEN-INCH RECORDS

If the rotating-drum film holder is used, with 10 or 15 in. of film on the drum, it will be necessary to use the pulley-and-gear-reduction unit, or its equivalent, to keep the film speed less than one-third of a revolution per second. With this reduction unit the 10-in. length of film could be adjusted to pass through in four steps of ten sec. each (or eight steps of five sec. each). A contact on the film holder opens the circuit at the end of the film and prevents further operation of the apparatus, until the film is changed.

### DAYLIGHT-LOADING FILM HOLDERS

The daylight-loading features of the film holders which are used on the Osiso have been used on the three-element portable oscillographs for some time,[4] and have proved to be very convenient and reliable.

The daylight-loading long-film attachment is shown in place in Fig. 11. This film holder uses standard roll film, 5 ft. long, intended for a $3\frac{1}{4}$ by $5\frac{1}{2}$ in. camera, or special 10-ft. films wound without the paper ordinarily used to back the film. This film holder passes the film half-way about the main drum and wraps it on the receiving spool. Furthermore, it does this with such uniform velocity that there is no bunching of waves even when there are as many as 100 cycles per inch length of film. For film speeds below 4 in. per sec., it is usually necessary to use the pulley-and-gear-reduction unit. At this speed the Osiso shows each cycle, more clearly than most oscillographs operating at from 2 to 5 times that speed. At this same speed, five records of six sec each could be obtained on one 10-ft. film. With the pulley-and-gear-reduction unit the total time could be increased to five minutes for 10 ft. of film, or 30 automatic operations of 10 sec. each, thus allowing 4 in. per record.

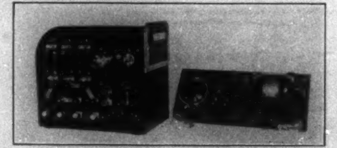


FIG. 10—THE POWER OSISO WITH ITS AUTOMATIC OPERATION PANEL AND SIX-VOLT MOTOR UNIT WITH DOUBLE-POLE SWITCH AND FIELD RHEOSTAT

The daylight-loading rotating-drum film holder takes 5 oscillograms, each 10 in. long, on one 10-exposure roll film. An observation window (to show the number printed on the opaque paper of the film) and a winding key make it possible to shift the film after each record is completed. The film may be removed without the use of a dark room, and sent to any photographer for development.

### FULL-CIRCUMFERENCE FILMS FOR CONTINUOUS OPERATION

A dark-room loading film holder is available taking special cut films (from Eastman No. 116 rolls) $15\frac{1}{4}$ in. long. This full-circumference film is essential for high-speed automatic operation, where the film runs from 5 to 20 rev. per min., continuously, day and night, until the chance disturbance closes the relay for an exposure under the instantaneously obtained desired brilliancy.

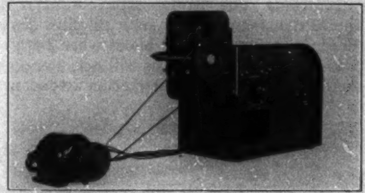


FIG. 11—THE POWER OSISO WITH DAYLIGHT-LOADING LONG FILM ATTACHMENT AND DRIVING MOTOR

The daylight-loading holder will also take a $15\frac{1}{4}$ in. film (cut from Eastman No. 130 roll) for high-speed operation on chance disturbances. A speed-reduction attachment, with a 5/6 revolution contact, may be supplied with any rotating-drum film holder. A small pinion and annular-gear give a speed reduction of 24 to 1, while the 3-in. pulley may be driven from the $\frac{3}{4}$ in. pulley of the motor and thus give a total reduction of 96 to 1. This permits adjustment of the film speed to 1 in. per sec., or 5 in. per sec. This is quite necessary for continuous operation.

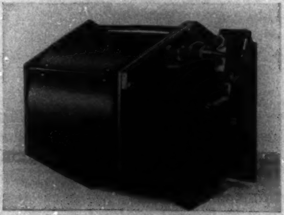


FIG. 12—DAYLIGHT-LOADING ROTATING-DRUM FILM HOLDER WITH PULLEY AND WORM CONTACT

### WORM CONTACT

All rotating-drum film holders may be equipped with a one-revolution contact, see Fig. 12. When taking a staged oscillogram this contact is connected in series with the Osiso lamp so as to give one revolution of light exposure on the drum, thus giving but one length of exposure on the film, at 600 rev. per min. or less. For delayed automatic operation, the film-holder contact is placed in series with the d-c. supply so as to prevent re-exposure of the film after one revolution. This outfit also gives excellent high-speed records of wave forms, telephone currents, inductive interference, vibrations in machines, etc.

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[4] *Expansion of Oscillography by the Portable Instrument*, J. W. Legg, TRANS., A. I. E. E., Vol. XLII, 1923, p. 381.

Fig. 13—Oscillogram of Instantaneous Watts, Volts, and Amperes. Very Distorted Condition

### Synchronously Driven Films

The light-weight drum of the dark-room loading film holder may be driven by a synchronous motor at 1200 rev. per min., or at 900 rev. per min., so as to obtain several 60-cycle waves on the one-film all in their proper time-phase relation. Fig. 13 shows an oscillogram of instantaneous watts, instantaneous volts, and distorted instantaneous amperes, on a 60-cycle line. As many as six waves may be taken on the one synchronously driven film by placing the one or two vibrators in the different circuits while the motor keeps the film in synchronism.

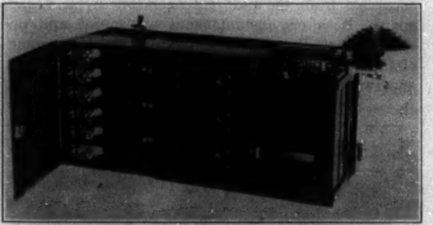

Fig. 14—Main Unit of Multi-Element Oscillograph. This is but 25 x 11 x 9.5 Inches Over-All

### Part III. The Multi-Element Oscillograph

The design of the three-element portable oscillograph described in the 1923 Transactions, page 381, and the six-element instrument (mentioned in the September 1926 Journal, p. 881) have been combined and extended to cover instruments with 3, 6, or 9 individual galvanometers, giving up to nine simultaneous records on the 7-in. wide film. The main unit (Fig. 14) of this multi-element oscillograph is but 25 in. long, 11 in. broad, and 9.5 in. high, over all, including everything but the film holder and its driving motor. In the 9-element outfit this case includes: a compact 6-element galvanometer with vertical vibrators; a compact 3-element galvanometer with horizontal vibrators and with reflecting prisms above each; complete optical system, incandescent lamp, and control switch; photographic shutter and remote-control mechanism; eleven dial control resistors; six knife switches; three toggle switches; and binding posts to connect into the various units of the 20,350 ohms of non-inductive resistance in the vibrator circuits.

The film holder and 6-volt shunt motor are all that is essential outside of the main case. A viewing attachment and three 2 to 20 ampere non-inductive shunts are also desirable. This whole oscillograph outfit, including the 6-volt motor, weighs from 90 to 120 lb., according to the number of galvanometer elements, resistors, film holders, etc., included. For many tests on transmission lines, this outfit replaces from two to four 3-element oscillographs, and in addition, gives records which are easier to analyze, since the records are all in the same time-phase relation. This outfit will operate from one large-size 6-volt storage battery.

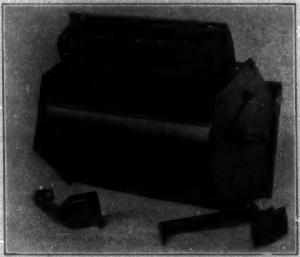

Fig. 15—Multi-Element Rotating Drum Film Holder Showing the Daylight-Loading Features

For this instrument there is provided a rotating-drum film holder similar to that used on the Osiso, only it is wider and will take either 7-in. or 3⅝ in. widths of film (Fig. 15). Each exposure is 10 in. in effective length and may cover a time interval of 0.04 sec. or greater. At this speed, 1200 ft. per min., the film obtains ample illumination from the 3-volt lamp when the latter is operated, momentarily, on 4 or 5 volts. Standard Eastman No. 115 roll films are used in this daylight-loading film holder. This does away with the necessity for a dark room at the place of tests, and permits any number of exposures to be made with one film holder. Each standard 6-exposure film gives three oscillograms.

If an exposure of more than one second is desired, a pulley-and-gear-reduction unit is necessary. This will give a film exposure range from 2 min. down to 0.04 sec. when operated by the sturdy 6-volt shunt motor supplied with every outfit. This slow-speed drive is very desirable for repeated automatic-operation on chance disturbances.

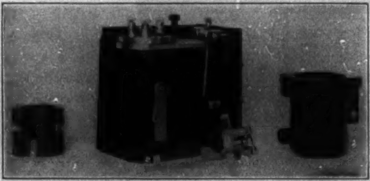

FIG. 16—PERMANENT MAGNET GALVANOMETER SHOWING MAGNET AND WELL AT EACH SIDE, AND VIBRATOR IN FOREGROUND

The long-film holder for this outfit is somewhat similar to that described before, only improvements have been added to make this outfit more reliable at higher speeds. Twenty-four-foot films, 6.5 in. wide, have been run through in as short a time as 4 sec. The maximum speed usually required is but 8 ft. in about five sec. Semi-special films 8 ft. long are available. Standard "Cirkut Outfit" films 3 ft. or 6 ft. long may be used, after slight modifications. This daylight-loading feature is very valuable in taking several successive tests. Half of the film holder remains on the oscillograph while the outer half is removed to reload. An annual gear and pinion reduce the speed of the film drum (12 in. in circumference) to 4 in. per revolution of the driving head instead of the 15 in. of the rotating-drum type. With this arrangement there is seldom need for the addition of the pulley-and-gear-reduction unit, except for very slow repeated automatic operation.

## VERTICAL GALVANOMETERS

Six vertical type galvanometers may be included in one frame. This 6-element galvanometer is but 3¼ by 3⅝ by 10⅜ in. over all, and is insulated to stand a test of 5000 volts between adjacent vibrator elements. Each element may be of the permanent magnet type or one or more elements may be of the instantaneous wattmeter type, having laminated-core electro-magnets.

A permanent magnet single-element galvanometer is shown partly disassembled in Fig. 16. A permanent magnet is shown externally at one side and a vibrator element at the other side. The galvanometer well is moulded in one piece, from moldata. The standard vibrator has a natural period of between 5000 and 6000 cycles per sec. undamped. When immersed in oil, within the galvanometer well, the vibrator has no natural period and responds, very satisfactorily, to frequencies up to 4000 cycles, and shows up much higher frequencies with a corresponding reduction in sensitivity. The standard vibrator has a resistance of approximately 1.3 ohms including the protective fuse, and requires approximately 0.12 amperes for one in. deflection of direct current. The sensitive vibrator requires approximately 0.03 ampere per in. deflection, and has a natural period of approximately 3000 cycles per sec., when undamped.

The instantaneous wattmeter, described with the power Osiso, may be used in place of one or more permanent magnet galvanometer units in the 6-element galvanometer frame. The only difference between the multi-element oscillograph and that of the Osiso is the difference in the power of the objective lens, which forms the window in front of the vibrator mirror. For most transmission-line studies, the total number of permanent-magnet and a-c. field galvanometers units may be six, within the one frame. The reaction between an instantaneous wattmeter and an adjacent galvanometer unit is so very small that it is negligible for all cases except where the film is driven very fast, and where it is desired to analyze the power wave for the higher harmonics. Where absolutely no reaction is required, the instantaneous wattmeter should be separated from the next galvanometer by a vacant space. With one instantaneous wattmeter and one vacant space, there could be a total of eight galvanometers in the one oscillograph. With two wattmeters, and two vacant spaces, there could still be a total of seven galvanometers. When vacant spaces are thus made available each vacant space may be traversed by a light beam, thereby adding a zero line, or timing line or other indicating or reference line on the photographic film. The whole nine beams of light will be found very valuable even when there are but six galvanometers in use.

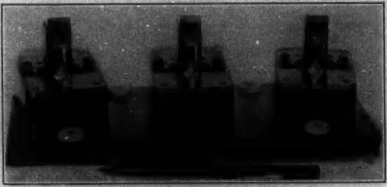

FIG. 17—HORIZONTAL GALVANOMETER, 7TH, 8TH, AND 9TH ELEMENTS

## HORIZONTAL GALVANOMETERS

The 7th, 8th, and 9th galvanometers are assembled on one base and are thus shown in Fig. 17. These galvanometers have their vibrators in a horizontal plane. Above each vibrator mirror is a reflecting prism which catches the incoming beam of light, from the optical box, throws it down to the vibrator mirror, and then throws it towards the photographic film after it is reflected from the vibrator and after it has twice passed through the objective lens. Each horizontal galvanometer is but 2 in. wide, 2¾ in. long, and 1¾ in. high, over-all. The reflecting prism above each galvanometer is so narrow that it does not interfere with the other beams of light which pass from the optical box to the six vertical galvanometers and thence forward to the photographic film. Nine galvanometers all in a row would be crowding things too much and would lessen the efficiency of the apparatus. The arrangement is very satisfactory with six vertical and three horizontal galvanometers, all within a cabinet whose outside width is but 11 in.

Fig. 18—Top View of Optical Box, Showing Prism and Slot Adjustments, and Tripping Magnet at Right

The horizontal galvanometers are oil tight and have the same sensitivity and frequency response as the other standard vibrators. They are supplied as instantaneous voltmeters or ammeters, but not as instantaneous wattmeters.

### The Nine-Beam Optical System

The whole optical system is complete in one removable box, except for the tiny mirrors and objective lenses in the galvanometers. This unit is shown in Fig. 18. The face of this unit forms the face of the oscillograph proper while the remainder is hidden within the micarta case of the oscillograph. Spherical condensing lenses are located beneath the optical floor (Fig. 19). These are used to concentrate the light from the 3-volt 9-ampere lamp on the vibrator mirrors. Nine reflecting prisms are located beneath the optical floor to direct this light to each individual vibrator mirror. An adjustable slot is located just beyond each reflecting prism to vary the width of the beam of light which passes to the moving film. Many adjustments, which might be accidentally thrown out of line in older instruments, have been made permanent in this apparatus by the proper design of each individual part. The adjustments which remain are very simple and are unaffected by ordinary handling of the instrument. The usual ball-and-socket adjustment of the reflecting prisms has been greatly improved so that there is no harmful sidewise motion. All adjustments are easily accessible by merely raising the front cover of the oscillograph proper. Levers are used as handles in making the adjustments. These point in the direction of the beams of light and so show, at a glance, the condition of adjustment.

The shutter mechanism is very nearly the same as described for the 3-element portable oscillograph, in the July 1920 A. I. E. E. Journal, on page 674 to 679 (of Vol. XXXIX). This shutter is mechanically operated to give one revolution of exposure to the fast rotating film. Being a focal-plane shutter, near the film, it more effectively keeps out all extraneous light from the film and permits the operator to glance at the illumination of the galvanometer without bothering with the shutter. A tripping magnet, remote-control switch, and cutout switch are included in the optical-box unit. The tripping magnet operates as soon as abnormal voltage is applied to the incandescent-lamp illuminant. A contactor, on the film-holder driving-head shaft, is set to operate the tripping magnet at any desired fraction of a revolution, ahead of the start of exposure on the film, equal in time to the time lag of the remote-controlled apparatus being studied. With this arrangement on staged tests, the remote-controlled power apparatus is started to function just in time so that its electrical phenomena will be photographed on the high-speed film, while the oscillograph lamp is at greatly abnormal brilliancy. The closing of the mechanical shutter, at the end of the film, also cuts off the lamp and hence the life of the lamp is conserved.

Fig. 19—Underside View of Optical Box

### The Control Unit for Lamp and Motor

The lamp-control panel (Fig. 20), is located on the front of the oscillograph in a cavity under the optical box. This unit is internally connected to the lamp, cut-out switch, tripping magnet, and contactor. Binding posts are provided to connect in the 6-volt storage battery and the 6-volt shunt motor. The lamp-control switch is set at 3 volts for viewing and calibrating purposes, and at 3.5, 4, or 5 volts for slow-speed or high-speed oscillograms. A double-pole knife switch is provided with an arrangement so that it may be closed by the operator pulling a cord from a distance. The closing of this switch starts up the motor, lights the lamp, starts the remote control mechanism functioning in the power apparatus, and causes an oscillogram to be taken which will show all the desired details of the operation of the power apparatus. The cut-out switch may be connected to stop the motor as well as to cut off the lamp, at the end of the exposure.

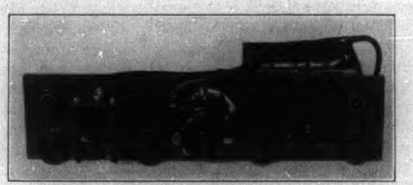

FIG. 20—CONTROL UNIT FOR LAMP AND MOTOR

### VIBRATOR RESISTORS

The standard resistor unit to control the 6-element galvanometer is shown in Fig. 21. This consists of four sections of 5000 ohms each and four sections with 50 ohms each. There are eight dial switches, to control these units, and six double-pole knife switches in the vibrator circuits. This whole resistor unit, with a total of 20,200 ohms of non-inductive resistance, fits under the galvanometer compartment in the main case of the oscillograph. This arrangement places sufficient resistance in three of the vibrator circuits to take transient potential peaks up to 1500 volts. One 5000-ohm unit acts as a spare and may be placed in series with any of these three vibrators so as to catch a peak of 3000 volts. This spare may be placed in series with a fourth low-resistance vibrator so as to record four simultaneous voltages. Likewise three of the low-resistance sections are permanently connected in series with three other vibrators. A fourth low-resistance section may be connected in series with any vibrator so as to give control of voltage in small steps.

A fuse is included in each vibrator circuit. This fuse is strung with vibrator ribbon. Since the ribbon of the fuse is in air and the ribbon of the vibrator is in oil, the fuse is a very good protection to the vibrator. A fuse is also made with a spring which keeps the fuse at a greater tension than the vibrator strip. With this arrangement the fuse is a perfect protector of the vibrator.

### HORIZONTAL RESISTOR

The resistor unit for the horizontal galvanometers is set in below the surface of the top of the oscillograph as shown in Fig. 14. This unit has three: 50-ohm rheostats, toggle switches, fuses, and sets of binding posts. This arrangement is suitable for controlling the 7th, 8th, and 9th vibrators when used to record current, or potentials below 10 volts. For power-circuit investigation: one of these vibrators may be used to record current from neutral to ground; another one mechanical movement of a circuit breaker, or relative displacement of certain parts; and the last, rev. per min., pressure, relay action, or some other function which may not be a pure electrical quantity.

### SIMULTANEOUS VIEWING AND PHOTOGRAPHING

An attachment has been developed[5] whereby the operator may continuously view several waves during the photographic exposure, as well as just previous to it. This is made possible by shifting three of the optical slots, with the levers marked "7," "8," and "9," shown in Fig. 18, so that three of the vertical galvanometers have two light beams apiece, one beam being reflected back to the film holder and the other to a reflecting prism and thence up to the viewing attachment in its new position over the optical box. Since there are but nine beams of light, the sum of the number of waves photographed and the number simultaneously viewed cannot be more than nine. Three of the waves viewed can be simultaneously photographed. When the six-element galvanometer is used without the 7th, 8th, and 9th galvanometers, it is possible both to photograph six waves and to view simultaneously three of them, and the viewing can be done both before and during the exposure. This simultaneous viewing and photographing attachment is very valuable for certain investigations where unusual conditions develop at irregular intervals.

### A-C. SUPPLY UNIT

A unit (Fig. 22) has been developed, with a transformer, a back-geared induction motor, proper fuses and switches, and convenient leads to connect this unit to the oscillograph. This outfit is on a base similar to that of the oscillograph case, but considerably shorter. The unit will operate from 100-120 volts or 200-240 volts supply of 25, 50, or 60 cycle frequency. This is a very desirable auxiliary for laboratory testing. It gives a speed range for the rotating film of from 685 rev. per min. down to 6.1 rev. per min. with 25 cycle supply, or 1010 to 15.1 rev. per min., with 60 cycle

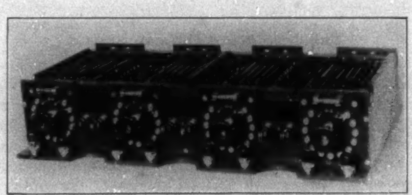

FIG. 21—STANDARD RESISTANCE UNIT TO CONTROL THE SIX ELEMENT GALVANOMETER

supply. This means from 0.04 sec. to 6.75 sec. per 10-in. length of film. With the long film holder, the lower limit of speed would be 720 sec. (or 12 min.) for 24 ft. of film. This outfit is particularly good for simultaneous viewing and will operate the viewing attachment continuously, and give excellent repetition of film speed when hundreds of oscillograms are to be taken with a constant time component on all films. The heavy-current low-voltage winding of the transformer normally gives 5 to 5.5 volts. This voltage is cut down by the lamp control switch in the oscillograph. This method of resistance control will not be satisfactory for automatic operation on chance disturbances. The 6-volt battery is better for this application.

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[5] See the authosr' discussion of Mr. Curtis' Paper in the A. I. E. E. TRANS., Vol. XLIV, 1925, pp. 271 and 272.

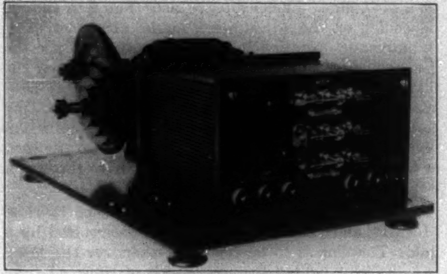

FIG. 22—A-C. SUPPLY UNIT WITH TRANSFORMER AND BACK-GEARED MOTOR

### RELAY FOR AUTOMATIC OPERATION

Single, automatic operation of any one of the incandescent-lamp portable oscillographs is extremely simple. Best results are obtained when the 3-volt lamp is thrown directly across two cells of a large lead-plate storage battery. A standard (type MC) multi-contact relay can be supplied with a special double coil which closes on 3 to 5 amperes a-c. and is held in by 4 to 6 volts d-c. until cut off by the oscillograph. This connects 4 volts directly to the lamp and 6 volts to the motor terminals. The standard cut-out switch on the oscillograph can be connected to drop out the relay and disconnect the battery at the end of the film. One set of contacts, on the relay, short circuits the a-c. pull-in coil after exciting the d-c. hold-in coil. Thus the relay will drop out at the same or lower current than that at which it pulled in. If the a-c. coil was not short circuited, it would not drop out until after the current was reduced to a much lower value than that which closed the relay. If all resistance is cut out of the circuit between the battery and the lamp (heavy leads must be used), then the lamp will attain full photographic brilliancy in less than ⅛ sec. after the closing of the relay contacts. The motor will attain its speed soon after, and a perfect record will be taken of the power surge which follows a chance disturbance in the power system, provided an abnormal current flowed through the relay coil located in the secondary of a standard current transformer.

### TERMINAL PANELS

When the oscillograph is to be used solely for a-c. power applications, and especially when the apparatus is to be kept on the line continuously, the 20,000-ohm non-inductive adjustable resistance may be omitted, and either fixed resistors, or oscillograph potential transformers, supplied in its place. Standard terminal panels can be used on the oscillograph when the large resistor unit is omitted. Oscillograph potential transformers (120 volts to 1.2 volts) can be mounted on these panels together with low resistance units, fuses, switches, protections, etc., according to the individual requirements for any particular service.

### FULL AUTOMATIC OPERATION UNIT

A full-automatic operation panel has been developed for the multi-element oscillograph. This is much more complete, and more costly in construction, than that used with the Power Osiso. This outfit replaces the standard control unit for lamp and motor, and operates automatically on chance disturbances in power lines. Fig. 23 shows the complete, internal, wiring diagram. The front of the panel looks much like the standard panel which is replaced. However, the lamp-control switch is replaced by a 6-circuit relay, the switch stop is replaced by a thermostatic relay, and the double-pole switch by a duration-control rheostat. The double-coil relay has four sets of making contacts and two sets of breaking contacts. One making contact, K-1, short circuits the 5-ampere a-c. pull-in coil (P). Two other making contacts (K-2 and K-5) are used in parallel to connect the lamp (L) across the 4 volts of the large storage battery. The remaining making contact is used to connect the motor to 6 volts from the battery. The two break contacts (K-3 and K-4) may be used to short circuit the current

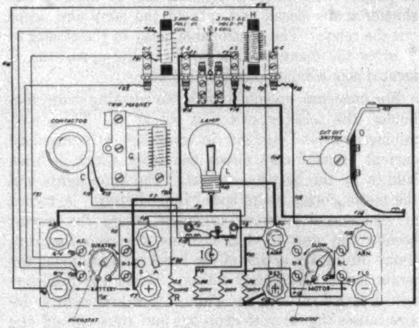

FIG. 23—DIAGRAMMATIC SKETCH OF THE FULL-AUTOMATIC OPERATION UNIT

coils of two instantaneous wattmeter galvanometers, if so desired.

The duration-rheostat controls the amount of heat that will be supplied to the bimetallic strip of the thermostatic relay (*T*). This thermostatic relay, together with the standard oscillograph contactor (*C*), controls the duration of each automatic operation. The cut-out switch (*O*) cuts off the lamp and the d-c. holding coil (*H*), at the end of film. The motor rheostat controls the shunt field current so as to obtain the proper speed of the film.

This apparatus may be used for three types of operation: First, for a *staged test*, such as deliberately throwing a short circuit on the power system to record what happens immediately before, during, and after the application of the short circuit. Second, for one or more automatic operations to be recorded on the ten-in. length of film on the rotating-drum holder. Third, for one or more (usually many) automatic operations to be recorded with the long film attachment so that each record may be of a definite length, both as regards time and distance traveled by the film. For *staged test*: The selector switch is thrown to *S*, the relay closes on d-c., the motor starts, the lamp lights, a few seconds later the remote-controlled apparatus is set into action, the proper time later the shutter opens and the exposure starts on the film, so as to give a few cycles record of open-circuit voltage followed by short-circuit conditions and the surge of power which follows. At the end of the film the shutter snaps closed and cuts off the lamp and drops out the relay. The controllable delay in the closing of *T* gives the operator time to leave the apparatus, if located near a dangerous short circuit.

For *automatic operation* with the rotating drum film holder, the selector switch is set at *A*. The determining over-load current (in secondary of a standard current transformer) closes the relay which is then held in by the battery current. The lamp lights and the motor comes up to speed immediately. A record of short-circuit current is made before the circuit breaker can start to clear the line, the recording continues during the action of the breakers and during the power surge which may follow. When the predetermined period of time has elapsed the thermostatic device causes the relay to drop out and thus cut off the lamp and motor. All is then ready for another chance overload. At the end of the film the shutter closes and knocks open the cut-out switch so no further operation will follow until the film is changed and the shutter reset.

### IDEAL REPEATED AUTOMATIC OPERATION

Repeated automatic operation with the long-film attachment can be made very definite as to time duration and exposed length of film by the action of the contactor *C* in series with the thermostatic contact of *T*. Every revolution of *C* represents ⅓ revolution of the main drum of the long-film holder, or 4 in. of film. By proper setting of the duration rheostat the thermostatic element can be made to operate before the driving head has made one revolution, so as to make each record 4 in. long. Likewise this may be set for two or for three revolutions, so as to give exactly 8 or 12 in. of record for each disturbance. This represents 24, 12, or 8 successive operations on chance disturbances for an 8-ft. film, or a maximum of 76 exposures on a 24-ft. film. Each exposure lasts from 2 to 15 sec., depending on the adjustments made. In most cases of automatic operation it will be necessary to use the gear-reduction unit between the 6-volt motor and the film driving head, in order to obtain a reasonably slow speed for the film, and corresponding low operating cost. However there is no need for this gear-reduction unit when it is desired to drive the film 8 in. per sec., or faster. This speed could be used to drive through a 3-ft. film in less than 5 sec.

A resistance between the binding posts marked "LAMP" and "RES" is normally short-circuited by a link. This link is to be removed whenever the lamp is to be kept lighted for any length of time, such as during visualization with the viewing attachment.

Great care should be used to eliminate all series resistance in the lamp circuit when it is desired to have the lamp come up to full brilliancy as soon as possible, as on automatic operation.

### APPARATUS REQUIRED FOR SATISFACTORY TESTS ON POWER LINES

The requirements of oscillograph apparatus may vary considerably according to the data required. The chief necessary parts might be summarized as follows:

A. At least three permanent magnet galvanometer elements and at least one instantaneous wattmeter element to show average watts, kv-a., and power factor. A total of nine elements may be included in one standard outfit.

B. A 20,000-ohm resistor unit with dial switches is very convenient for general testing with six elements. For power tests it may be possible to use 120 to 1.2 volt potential transformers to replace the high resistors. The three additional elements seldom require more than 50 ohms adjustment apiece, such as is supplied in the top panel described.

C. No special relays are required for general testing and for staged tests. The lamp-control panel of the standard oscillograph is well suited to all such tests. When the oscillograph is to be used mainly for automatic operation on chance disturbances it is very convenient to have the full-automatic panel designed for this purpose. However, relays may be used external to the standard outfit and give fairly satisfactory results.

D. A daylight-loading high-speed rotating-drum film holder is very desirable for general testing, but may be replaced by a daylight-loading long-film holder for repeated automatic operation on chance disturbances. The latter will take films up to 24 ft. in length.

E. A shutter mechanism, remote-control and lamp-extinguishing switches are very valuable for staged tests, but are not needed when the outfit is to be used solely for automatic operation with the long film holder.

F. For purely laboratory testing, it is convenient to use an a-c. supply unit with transformer and back-geared induction motor for driving the film at any desired speed.

G. A sturdy 6-volt shunt motor has proved to be so valuable that it is included in every outfit. This motor is ideal for automatic operation on chance overloads in power systems.

H. Anyone who obtains a 3-element oscillograph will appreciate the fact that it may be made into a 6- or 9-element outfit whenever needed.

I. Mere compactness of apparatus amounts to little compared with the increased reliability and ease of operation which is insured by proper design and construction of these instruments.

Many oscillographs of this general type have been used throughout this country, Japan, and Europe.

## Discussion

**R. D. Evans:** There is one point I should like to emphasize in connection with the instruments described, that is the use of the *power* or *watt element.* We are so accustomed to oscillographic records of voltage and current that a power element record seems a little strange. Power records are, however, so useful for determining what has happened on power systems, that I am sure the use of the power element will find wide application.

# High-Voltage Oil Circuit Breakers for Transmission Networks

BY ROY WILKINS[1] and E. A. CRELLIN[1]

Member, A. I. E. E. Member, A. I. E. E.

THE standards of the American Institute of Electrical Engineers define an oil circuit breaker as a "device (other than a fuse) constructed primarily for the interruption, in oil, of a circuit under infrequent abnormal conditions." Common usage, however, has sanctioned the use of the term "circuit breaker" as applying to a device for the regular and usual interruption of an energized circuit as distinguished from a switch used only for opening circuits which are deenergized or not carrying load. This paper will consider only high-voltage oil circuit breakers, the term "high voltage" being taken as applying to potentials of 25,000 volts or above.

The fundamental purpose of a high-voltage transmission network is to deliver power with a maximum of reliability at a minimum expense.

The high-voltage oil circuit breaker is an integral part of a transmission network. It is purchased not to demonstrate whether or not it will fail under operating conditions, but to insure service under both normal and abnormal conditions.

In every paper on transmission line stability presented before the Institute during the past five years, the importance of fast and accurate switching has been emphasized. The present paper proposes to outline in a general way how present day high-voltage oil circuit breakers fulfil some of the operating requirements of transmission networks.

It may be said that oil circuit breakers are in use today only because no better substitute has been developed. In them, the function of the oil is to insulate the contacts one from another and from the tank or ground. Mineral oils with a relatively high flash point are the only insulating mediums thus far available. It must be noted, however, that during the time of arcing the oil is a decided detriment to the breaker. It becomes volatilized and builds up excessive pressures in the container, and it becomes ionized and forms a conducting path which aids rather than hinders the arc. If it were possible to so construct a breaker, it would be better to separate the contacts the required distance and then introduce the oil at the zero point on the voltage wave. This is not a practical possibility and it is therefore necessary to have the contacts immersed in oil at all times.

Many substitutes for oil have been proposed and tried with varying degrees of success, and of these a high vacuum seems to offer the greatest possibility of an ultimate solution to the problem.[2] A one-half inch travel of contacts in a high vacuum is equivalent to a great many inches of travel under oil, and many possibilities present themselves. The practical application of the knowledge is a real problem. An exceptionally high vacuum must be continually maintained under service conditions, and means must be developed for moving the breaker contacts the necessary inch or so within this vacuum before the switch can be made ready for general application. Of the other alternatives to oil, mostly hydrocarbons, which have been tried, none so far has been able to supplant the petroleum derivatives except for very special uses and even then only to a limited extent.

From the foregoing it is seen that there is no immediate prospect of using any current interrupting device for the control of high-voltage transmission networks other than the oil circuit breaker using a mineral oil as the insulating medium. It must therefore be the foundation upon which to base the immediate developments to secure improvements which will better fit it for the duties it must perform. That improvements are necessary and urgently needed is obvious to all operating men.[3]

The object of an oil circuit breaker is to interrupt current. For the purpose of this discusssion the characteristics of the interruption may be divided into two general groups, which may each be further subdivided for special consideration as follows:

I Characteristics influenced by the operation of the oil circuit breaker.
  a. Speed of break
  b. Current (to a limited extent) to be interrupted.

II Characteristics dependent upon the connected circuit.
  a. Power factor,
  b. Recovery voltage,
  c. Phase balancing,
  d. Growth and decay of current values,
  e. Resonance.

The subheading, I-a, may be still further subdivided for a study of the manner in which the speed of break is controlled:

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*Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., Sept. 13-16, 1927.*

[2] *Vacuum Switching Experiments at California Institute of Technology*, R. W. Sorensen and H. E. Mendenhall, A. I. E. E. JOURNAL, December, 1926, p. 1203.

[3] A. I. E. E. TRANS., Vol. 43, 1924, pp. 656-657. and *Elec. World*, Feb. 5, 1927, p. 302.

I-a. Speed of break.
  1. Speeding up moving parts by,
    a. Spring retracted contacts,
    b. Accelerating springs,
    c. Quick break contacts,
    d. Explosion chamber contacts.
  2. Multiple breaks.

The manner in which the speed of break is affected by the several methods listed above will be considered as exemplified in present day operating practise.

a. Spring retracted contacts were first used extensively on oil immersed fuses which were in reality oil circuit breakers with a fuse as the tripping mechanism. They were developed and used in Europe prior to 1904 and have been thoroughly described in the technical journals of the time.[4] Letters patent covering this type of apparatus were granted in the United States in 1905.[5] This type of equipment is doubly interesting at the present time because the surviving examples represent at the same time the highest contact speed and the smallest physical dimensions of commercial current interrupting devices for use on high-voltage circuits. The speed of break attained in a 1½-ampere, oil filled spring retracted fuse with 7-lb. (3.17 kg.) pull is approximately 40 ft. per sec. (13.1 m. per sec.). An example of its performance with 1600 ohms resistance in series is given in Fig. 1 and with 300 ohms series resistance in Fig. 2. Both tests were made in the short-circuited phase to ground connection of a grounded Y 110-kv. circuit.

Fig. 1

Fig. 2

b. Accelerating springs are used at present on most of the high-voltage oil circuit breakers. They may be compression or tension springs or both, and in some cases both types may be found in the same breaker. Such springs are for the most part extended or compressed, (depending upon the type), by the final action of the closing mechanism of the breaker and serve both as a damping agent on the closing stroke and for acceleration of the contacts on opening. In certain cases, the contacts themselves serve such a purpose, as for instance in the Westinghouse butt contacts, which are spring-supported or the condit contacts which are of laminated leaf copper type. The effect of these contacts can be seen clearly in the accelerated travel of the moving member, which slows down again after the contacts part. See Fig. 6.

There are two major objections to the accelerating springs in general use. First, their effect is minor so far as a reasonable amount of speed in concerned, the maximum recorded being about one-half ft. per sec. (15.2 cm. per sec.); and second, they absorb energy at a time on the closing stroke when it cannot well be spared from most types of closing mechanisms. If greatly strengthened, they give rise to uncertain closing and hair trigger adjustments, already too much condemned by operating engineers to require further discussion. Suffice it to say that present day breakers require too many critical adjustments, and development must be toward a reduction in their number rather than any tendency to make them more critical.

c. Quick break contacts usually take the form of auxiliary contacts and serve two purposes,—first, to increase the separation betwen contacts in a given time, *i. e.*, to reduce the time of arcing, and second, to preserve the main contact surface by breaking the arc on replaceable auxiliary contacts.

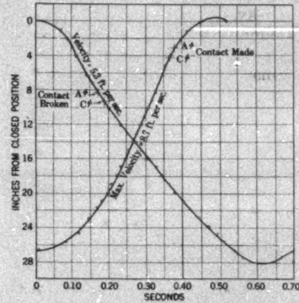

Fig. 3—Calibration of Position Indicator—110-Kv., 400-Ampere Oil Circuit Breaker

Vaca—Dixon Substation—June 20, 1926

From an operating standpoint the time and energy required to operate the quick breaks is an advantage to the oil circuit breaker, gained at the expense of the system on which it operates. This comes about by reason of the fact that all varieties of quick break contacts now available delay the opening time until the contacts have traveled a sufficient distance to bring the quick break into action. Figs. 3 and 4 show the speed time curve of a Pacific Electric Manufacturing Company, 110-kv., 400-ampere, six-break, oil circuit breaker with contacts arranged as shown in Fig. 5. In this case, the main contacts part after 3 or 4 in. (7.5 or 10 cm.) of travel from the closed position, whereas the arcing contacts do not part until 8 or 10 in., (20 or 25 cm.) of travel has been obtained. This requires 0.075 sec. or more than 4 cycles on a 60-cycle system.

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[4] *Elektrotech. Zeitsch.*, June 9, 1904, F. Collischonn.

[5] Patent No. 781,347 to Christian Kramer, Jan. 31, 1905.

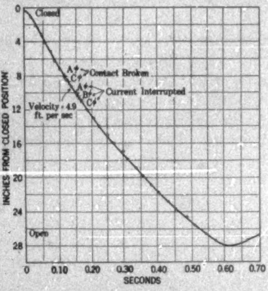


FIG. 4—INTERRUPTION OF PIT LINE CHARGING CURRENT WITH 110-KV., 400-AMPERE OIL CIRCUIT BREAKER

Vaca—Dixon Substation—July 12, 1926

Fig. 6 shows the speed—time curve for a Westinghouse Type G-2, 187-kv. oil circuit breaker of the type used on a 220-kv. grounded Y system in which the quick break contacts have the form shown in Fig. 7. With this breaker, the main contacts part about 1½ in., (4 cm.) from the closed position and the quick break auxiliary contacts about 10 in. (25 cm.) from the closed position. This requires about 0.25 sec. or 15 cycles on a 60-cycle system. The speed obtained on the quick break contacts themselves is about twice that of the main contacts so that the arc when started is extended at about three times the main contact speed.

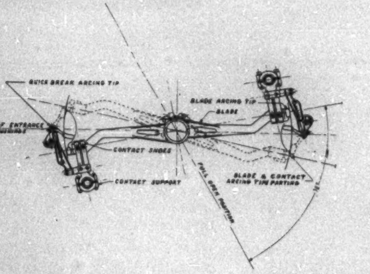

QUICK BREAK ARCING TIP
BLADE ARCING TIP
BLADE
℄ OF ENTRANCE BUSHING
CONTACT SHOES
CONTACT SUPPORT
FULL OPEN POSITION
BLADE & CONTACT ARCING TIPS PARTING
10"

FIG. 5—DETAILS OF CONTACTS, PACIFIC ELECTRIC OIL CIRCUIT BREAKER

d. Increased contact speed may also be gained through the use of the explosion chamber type of contacts. These are a development of the original Type *H* oil circuit breaker manufactured by the General Electric Company, and may be found in the high interrupting

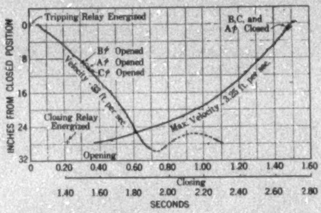
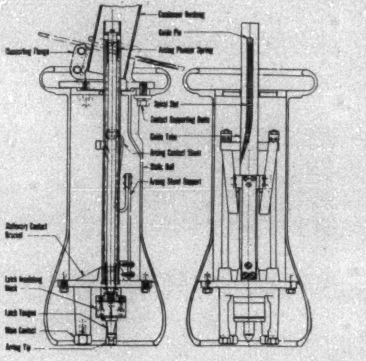
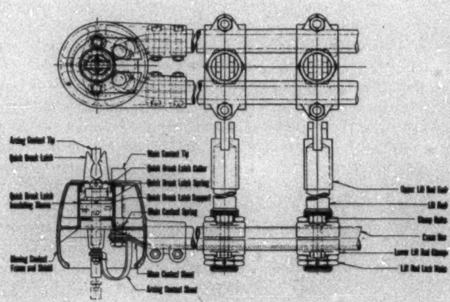


FIG. 6—POSITION INDICATOR CALIBRATION

Westinghouse type G-2, oil circuit breaker, with rotating release arcing tips, at Vaca—Dixon Substation—June 26, 1926


Condenser Bushing
Guide Pin
Arcing Plunger Spring
Supporting Flange
Special Stud
Contact Supporting Bolts
Guide Tube
Arcing Contact Shield
Static Rod
Arcing Shield Support
Stationary Contact Bracket
Latch Insulating Block
Latch Tongue
Main Contact
Arcing Tip

(Stationary Member)


Arcing Contact Tip
Quick Break Latch
Quick Break Latch Insulating Sleeve
Moving Contact Frame and Shield
Main Contact Tip
Quick Break Latch Collar
Quick Break Latch Spring
Quick Break Latch Support
Main Contact Spring
Main Contact Shield
Arcing Contact Shield
Upper Lift Rod Shaft
Lift Rod
Clamp Bolts
Cross Bar
Lower Lift Rod Clamp
Lift Rod Lock Nuts

(Moving Member)

FIG. 7—BAYONET-TYPE HIGH-SPEED CONTACT (ROTARY FORM)

capacity breakers of the General Electric Company in the United States, and its affiliated companies, notably the A. E. G., in Europe. The principle of the explosion chamber contact is illustrated in Fig. 8 and is too well known to require any extended description here.

In this type of contact the speed of break is obtained by virtue of the gas pressure in the contact chamber acting on the rod as a piston. The gas pressure is generated by the arc acting on the oil within the explosion chamber and depends upon the clearance between the contact rod and the explosion pot entrance bushing and the amount of oil volatilized. The amount of oil volatilized depends upon the current in the arc and the time of arcing. This means that high currents will cause increased contact speed over lower currents.

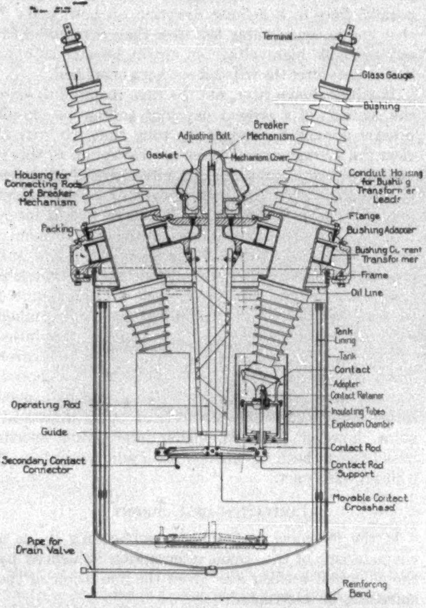

Terminal
Glass Gauge
Bushing
Breaker Mechanism
Adjusting Bolt
Gasket
Mechanism Cover
Housing for Connecting Rods of Breaker Mechanism
Conduit Housing for Bushing Transformer Leads
Flange
Packing
Bushing Adapter
Bushing Current Transformer
Frame
Oil Line
Tank Lining
Tank
Contact
Adapter
Contact Retainer
Operating Rod
Insulating Tubes
Explosion Chamber
Guide
Contact Rod
Secondary Contact Connector
Contact Rod Support
Movable Contact Crosshead
Pipe for Drain Valve
Reinforcing Band

FIG. 8—TYPICAL OUTLINE OF SINGLE-POLE ELEMENT OIL CIRCUIT BREAKER, 110,000 VOLTS AND ABOVE

Fig. 9 shows the speed—time curve of a General Electric F H K O-36-33C, 115-kv., oil circuit breaker at no-load, and Fig. 10 shows the speed—time curves for the same breaker when interrupting 300 amperes of line charging current. In this type of contact the clearances are determined by the maximum amount of current to be interrupted and the maximum speed the contact member is permitted to attain. In the example given above, the maximum speed was 5.5 ft. per sec. (1.8 m. per sec.) while in the extensive Canton tests[6] the contact speeds were between 6 and 7 ft. per sec. (2 and 2.3 m. per sec.). The contact speeds attained at the Alabama Power Company tests[7] on explosion chamber breakers were between 4.75 and 6.6 ft. (1.56 and 2.16 m. per sec.). This type of breaker obtains increased contact speed at the expense of the oil in the circuit breaker.

The breakers thus far considered have all been of the two-break type, and the total length of arc in all makes is approximately the same. The contact speeds are also of the same order and range from 3.5 ft. (1.15 m.) per sec. to somewhat less than 7 ft. (2.3 m.) per sec. In order to better appreciate what these speeds represent, it may be well to convert them to mi. per hr., a term universally familiar to all. Thus we see that 3.5 ft. (1.15 m.) per sec. is only 2.4 mi. (3.86 km.) per hr., 5 ft. (1.64 m.) per sec. is 3.41 mi. (5.5 km.) per hr. and 10 ft. (3.28 m.) per sec., 6.82 mi. (11 km.) per hr. which is only slightly above the speed of a brisk walk. Present day high-speed d-c. circuit breakers have a speed of approximately 200 ft. (65.6 m.) per sec.

Speed of contact travel is the only feature of the breaker which may be varied to reduce the time of arcing, and when it is considered that it is at present usual to ask for interrupting capacities of a million kv-a. or more, it would seem logical to greatly increase the speed of contact travel. The effect of increased contact speed will be discussed later.

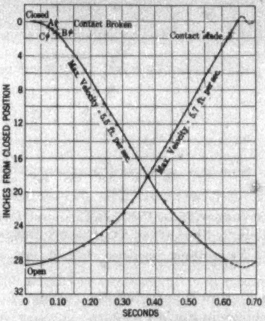


FIG. 9—CALIBRATION OF POSITION INDICATOR—115-KV., 400-AMPERE OIL CIRCUIT BREAKER
Vaca-Dixon Substation—July 10, 1926

Under the heading I-a, Speed of break, there still remains the consideration of the second subdivision, Multiple breaks. By common usage the term multiple break has been considered to apply to circuit breakers employing more than two simultaneous breaks in series

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6. JOURNAL A. I. E. E. July, 1927, p. 698, *Tests on Oil Circuit Breakers*, by Sporn and St. Clair.

7. J. D. Hilliard, *Circuit Breaker Tests at Bessemer, Ala.*, TRANS. A. I. E. E., 1924, p. 626.

to interrupt the circuit. American manufacturers of this type of breaker are the Condit Electric Manufacturing Company (Brown Boveri type) the Kelman Electric and Manufacturing Company and the Pacific Electric Manufacturing Company. The Brown Boveri switch tested at Canton[8] was an imported breaker, but almost identical with the American built breakers of the same design. This was a type A F 24/1A, 150-kv. breaker with ten breaks in series per pole. It had a contact speed of from 1.7 to 2.2 ft. (0.56 to 0.72 m.) per sec. and a contact travel of a little less than one foot, (0.3 m.).

The Pacific Electric breaker has six breaks in series per pole, the contacts rotating to make a horizontal break. The speed—time characteristics of this breaker with a solenoid operating mechanism are shown in Fig. 4. The most recent switches of this company are equipped with a motor-wound spring-type operator which has increased its speed of operation to give a contact travel of approximately 15 ft. (5 m.) per sec. with speed—time characteristic curves of the same shape as shown in Fig. 4.

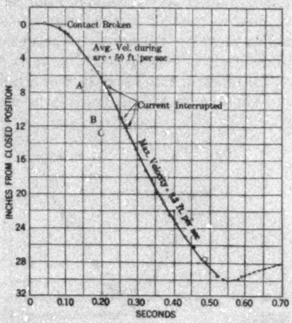

Fig. 10—Interruption of Pit Line Charging Current with 115-Kv., 400-Ampere Oil Circuit Breaker

Vaca—Dixon Substation—July 10, 1926

Kelman breakers also employ a six-break contact which is controlled through a pantograph mechanism to make a horizontal linear break. The breaker is solenoid operated, and has a contact travel of approximately 3.2 ft. (1 m.) per sec.

The importance of speed in clearing trouble in a high-voltage transmission network cannot be too strongly emphasized. As systems grow in size and the amounts of power available at a fault increase, it becomes more and more necessary to isolate the fault in the shortest possible time. With the large amounts of power available, great damage is done in a very short space of time and the very existence of the network depends upon the quickness and accuracy of the switching.

Relays have been developed and applied to line protection to such an extent that it is now practicable to relay a line so that troubles causing a flashover can be cleared before material damage is done to the line insulators or conductor more than 90 per cent of the time. Relays are now in operation which will close their contacts selectively on grounds on one of a pair of parallel lines in a definite direction on both ends of that line in considerably less time than is required for any available high-voltage oil circuit breaker to open its contacts after the trip coil has been energized.

It will be shown later that the time required to open the contacts of a present day high-voltage oil circuit breaker is roughly one-half the total time required to clear the average case of trouble. Exception to this is made in the case of the breakers with explosion chamber type contacts where the time is greater or less dependent upon the particular design and the current to be interrupted. It is therefore evident that the time consumed by the relays in discriminating between circuits and starting the necessary operations to trip the switch is approximately only one-third of the total time required to clear the circuit. The balance of the time is taken by the oil circuit breaker itself in completing the interruption and is unnecessarily long. That increased speed is desirable seems to be universally accepted. The best method of achieving this increased speed seems very much debated. From an operating standpoint, however obtained, higher interrupting speeds would benefit both the breaker itself and the system of which it was a part.

### Limitation of Current

In the foregoing outline under subheading (b) as a characteristic of the circuit interruption influenced by the oil circuit breaker was given the limitation of the current to be interrupted.

In such breakers as have this feature incorporated, it is usually accomplished by the insertion of resistance into the circuit before the final rupture takes place. European breakers use this feature much more often than those manufactured in America, one reason being that the greater proportion of European oil circuit breakers are multiple contact and lend themselves particularly well to such treatment.

The mechanical design of high-voltage oil circuit breakers is not yet advanced to a point where the resistance feature can be added without reducing the mechanical reliability of the breaker below a safe minimum in many cases.

However, low-voltage circuits for heavy duty are customarily equipped with external reactors to reduce the duty on the oil circuit breaker and are considered sound practise even though they entail a continuous loss often for the sole purpose of protecting the oil circuit breaker momentarily during trouble.

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[8] Sporn and St. Clair., *Tests on Oil Circuit Breakers*, Journal A. I. E. E., July, 1927, p. 698.

The expense and operating difficulties attending the use of external reactors for high-voltage work has prohibited their use for 60 kv. or above, except in a few isolated cases. The mechanical difficulties attending their use internally on a two break oil circuit breaker have likewise prohibited their use in that direction in this country.

### CHARACTERISTICS DEPENDENT UPON THE CONNECTED CIRCUIT

As subheadings under those characteristics over which the oil circuit breaker has no control are grouped: (a) power factor, (b) recovery voltage, together with others to be considered later.

Because of the fact that the current in an a-c. circuit is broken at or near the zero of the current wave the duty on the breaker is least at unity power factor since the voltage across the contacts is also zero at that time. With a decrease in power factor two things happen:

First: The voltage available to strike across the gap and reestablish the arc is higher being a maximum at or near zero power factor since the voltage is a maximum when the current is zero at that time.

Second: Since the character of the circuit interrupted determines the character of the voltage wave across the contacts, the arc voltage on inductive circuits has the characteristic horns as discussed in many texts.[9]

These horns for metallic electrodes under oil are very sharp, frequently too sharp to be recorded satisfactorily on the commercial oscillograph and are often equal to or slightly greater than the nominal circuit voltage at the time of interruption.

Contrary to the usual idea, system stability tests have demonstrated that in practise the power factor of a ground on a high-tension network may have been reasonably good and operating practise has determined also that by far the major portion of high tension network troubles are from conductor to ground.

In practise, therefore, the power factor of the circuit, while important, is not vital to an oil circuit breaker with any reasonable margin of safety except in special cases which will be considered later. Coupled with power factor is recovery voltage usually defined as the voltage across the oil circuit breaker contacts in the first half cycle after the circuit is interrupted.

The only thing definitely established regarding recovery voltage on an operating network is that it is not the simple vector relation of normal voltages that a single generator gives on test. All of the transient characteristics of the connected equipment influence it sometimes for several cycles after the arc has cleared.

FIG. 11—INTERRUPTION OF SINGLE-PHASE GROUND ON PIT LINE NO. 1 (SYSTEM CONNECTED)

Vaca—Dixon Substation—July 9, 1926
Y — B P contacts open
El. 1—Position indicator
El. 2—Arc volts B phase
El. 3—B phase current
El. 4—50-cycle timing

### PHASE BALANCING AND GROWTH AND DECAY OF CURRENT VALUES

In low-voltage networks and particularly in oil circuit breaker tests on a single generator the current to be interrupted begins to decrease after the first half cycle of short circuit. It is therefore, as a rule, easier for the oil circuit breaker to clear the circuit several cycles after the short circuit is applied.

Most troubles on such generators and networks are between phases so that such tests represent a practical operating condition.

High-voltage network troubles are more often from wire to ground; on the sytem of the Pacific Gas and Electric Company for instance, on 60 kv. and above, over 95 per cent of all line trouble is from phase to ground. For such conditions the initial short circuit current may be only a fraction of the final value to be interrupted.

Fig. 11 gives an oscillograph record of a wire to ground short circuit on one of two parallel 220-kv. lines with the system in normal operation cleared by relay in the usual way, leaving the second line in service. The current in this case increased for some 5 or 6 cycles and was then practically constant until interrupted. This is due to the so-called phase balancing action and in some cases has given as high as a 2 to 1 ratio between initial and maximum amperes. The same thing takes place if the several phases of an oil circuit breaker do not interrupt the circuit simultaneously although this trouble is largely eliminated from present day oil circuit breakers.[10]

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[9] Alternating Current Phenomena, C. P. Steinmetz, Pages 353-357.

## RESONANCE

Of all the phenomena occurring during the interruption of a high-tension circuit as part of an operating network, there remains the one probably the least understood,—resonance. At the instant the contacts part, an arc is established. It has a so-called negative resistance due to the fact that the initial stream of ions and electrons under the influence of a high potential gradient cause additional ions and electrons by collision. This in effect increases the area of the arc and decreases the resistance.

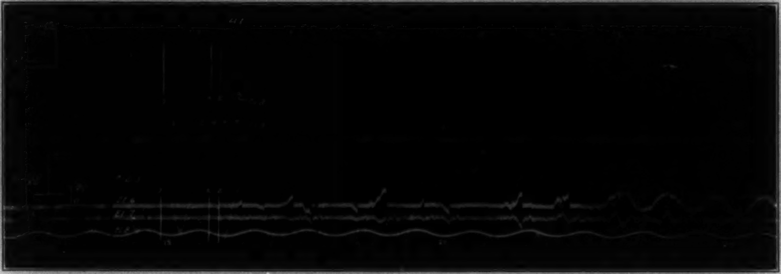

FIG. 12—PIT LINE CHARGING CURRENT INTERRUPTION AT 220 KV.

Vaca—Dixon Substation—June 26, 1926
X—A-phase contacts open
Y — B phase Z — C phase
El. 1—Position indicator
El. 2—C phase current
El. 3—A phase current
El. 4—50-cycle timing
El. 5—B phase current
El. 6—Arc volts B phase
El. 7—Arc watts B phase
El. 8—50-cycle timing

At the start of the break there is a relatively low potential across the arc and the effect of arc voltage is scarcely noticeable. As the contacts part the voltage across the arc increases and the current growth for each cycle is determined more and more by the characteristics of the connected circuits frequently differing greatly from the system frequency.

This ability of the arc to convert from one frequency to another is well known in communication but is little appreciated by transmission engineers and practically no data on the effect of series arcs in a circuit containing capacity and reactance are available.[11]

This has an immediate and practical application in high-tension oil circuit breaker practise because on every line that is cleared in trouble to ground at least two phases at one end must interrupt charging current which may or may not be the nominal charging current of that line.

In Fig. 11 was given a record of the interruption of a single-phase 220-kv. ground of some 2430 amperes.

Fig. 12 gives the record of the same oil circuit breaker on the same 202-mi. line interrupting 156 amperes of charging current at 220 kv.

The length of arc, slightly under 19 in. per contact, was the same, the contact burning the same so far as visual inspection could determine, and the deterioration of the oil the same. Figs. 13 and 14 give these plotted in the form of curves.

It is to be noted that after the first two cycles the current builds up at the natural period of the line to values much in excess of the normal 60-cycle charging current, the speed of current growth being greater for short sections of line since the characteristics change for them.

In practise such records have been taken for several makes of 110-kv. oil circuit breakers for identical conditions using the several methods of increasing contact speed from two break breakers with a speed of less than 4 ft. per sec. per contact to 6-break breakers with a speed of 15 ft. per sec. per contact and a range of arcing time from 12 cycles on the slower speed to 2 cycles on the higher speed.

The total arc length increases for a given duty on most types as the speed increases at some rate less than the speed increase, *i. e.*, a 6-break oil circuit breaker has a greater total arc length, but a much shorter length per contact than a two-break oil circuit breaker for the same duty.

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[10] *Practical Aspects of System Stability*, R. Wilkins, A. I. E. E. TRANS., Vol. XLV, 1926, p. 41, (Fig. 7).

[11] C. P. Steinmetz, *Frequency Conversion by third Class Conductor*, A. I. E. E. TRANS., Vol. XLII, 1923, p. 470.

The important point often overlooked is that the high-speed breaker clears the disturbance in much less time with much less damage both to the system and to the breaker.

There is no virtue in making an elaborate contact arrangement and then slowing the whole mechanism down to the same total speed as a simple one break breaker. But a breaker which will clear a given trouble in one or two cycles is a much more satisfactory piece of apparatus than one requiring 15 cycles, provided it can be properly relayed and made to stay together.

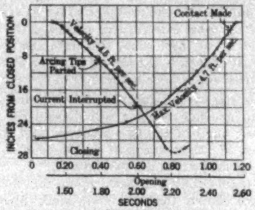

FIG. 13—SINGLE-PHASE GROUND ON PIT LINE NO. 1

Equipped with rotating release arcing tips. Breaker tripped out by station relays. Line connected to System, at Vaca—Dixon Substation—July 9, 1926

## CONCLUSIONS

Throughout this paper the viewpoint on controversial subjects has been from the practical side; that is to say, from the position of the operating man rather than the manufacturer. This as is it should be, for design must meet the requirements of the operating man who purchases and uses the apparatus.

The primary assumption has been made that the function of a transmission network is to deliver power with a maximum of reliability at a minimum expense. The oil circuit breaker is an integral part of the network and has a particular and very important function to perform.

Engineers engaged in the design of transmission networks must now plan the network to operate in such a manner that it will not overstep the capacities of the oil circuit breakers installed. These capacities are not definitely known and therefore large factors of safety must be allowed and unnecessary expense incurred.

This is especially true in very high-voltage transmission lines, where both carrying capacity and stability are greatly improved if the lines can be broken up into sections by switching stations and only a relatively small section isolated to clear up trouble. Such a plan is not generally carried out because of the operating limitations and great cost of high-voltage oil circuit breakers. The oil circuit breaker is therefore the limiting feature to the securing of the best possible operating results in electric transmission developments involving many millions of dollars.

With the increase in transmission voltage and the large concentrations of power, there has come a new set of problems not previously encountered. The problems of transmission line stability and continuity of service are of the utmost importance because outages render large blocks of power unproductive of revenue and may cause financial loss to consumers dependent upon continuous service. The position which the oil circuit breakers hold in these problems is becoming more generally realized, their faults and shortcomings recognized and most important of all, their economic relation to the rest of the development is being clarified. This has taken time, for engineers and operators have formed the habit of unconsciously basing their decision around oil circuit breaker limitations. They had to be on the safe side, and what would have been the best solution of a problem may have been discarded in place of a plan less favorable from economic or operating results, but more sure of success because the circuit breakers could not be considered as highly reliable pieces of apparatus to guarantee the carrying out of the most desirable plan.

Certain fundamental requirements may be set down as essential in an oil circuit breaker for use on high-voltage transmission networks. To meet these requirements with present day knowledge of oil circuit breaker design requires a composite breaker embodying the strong points to be found in the designs of the several manufacturers. Briefly, these requirements are:

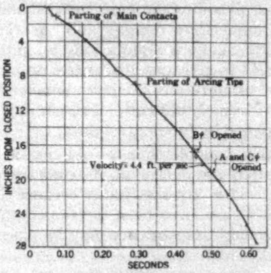

FIG. 14—PIT LINE NO. 1 CHARGING CURRENT INTERRUPTION, WITH WESTINGHOUSE TYPE G-2 OIL CIRCUIT BREAKER

Equipped with rotating release arcing tips at Vaca-Dixon Substation, June 26, 1926

1. The total operating time for a complete "open-close-open" cycle of operations at rated current, and voltage shall not be more than 0.2 sec.
2. The arcing time shall approach as close as possible to the ideal of one-half cycle.
3. The energy for the switch operator shall be stored and available for instantaneous release. The mechanism should not have a power demand in excess of one kw.

4. The breaker shall be capable of completing 100 normal operating cycles before any inspections or adjustments are necessary. (If requirements 1 and 2 are met successfully, there should be no trouble in reaching 1000.)

5. The breaker shall be so designed that it can be installed, adjusted, and maintained by the average mechanic without especial training in oil circuit breaker technique.

The growing knowledge of the important part played by the oil circuit breaker in a transmissiion network is stimulating investigations on the part of the operating companies to satisfy themselves as to the best circuit breaker for use on a given system. As has been previously stated, it is economically unfeasible for each manufacturer to maintain equipment for the testing of oil circuit breakers with a rating of 2,000,000 or more kv-a. at 220,000 volts. Also these tests at the manufacturers' plants are not conclusive for it is impossible to duplicate the conditions met on an extensive, interconnected transmission network, where recovery voltage, resonance, surges, etc., are variable and indeterminate.

The only way in which it is now possible for an operating company to satisfy itself of the suitability of any theory of circuit breaker design, is to conduct carefully supervised tests on its own system. This requires a maximum of courage, but if reliable service is the ultimate goal, all equipment must be tried and found not wanting. Competitive designs and theories, coupled with a wide range in price quotations, all in the face of a positive refusal to give any guarantees on performance, make the selection of an oil circuit breaker for a given installation extremely difficult. Present day knowledge must be amplified by further test data.

It is entirely possible that the oil circuit breaker as now known, may not be the ultimate device for opening a-c. circuits. They are used today because they are the only devices which have been developed to the point where a reasonable dependence may be placed on their operation.

The immediate problem is to combine in one oil circuit breaker all of the good features now available in the designs of the several manufacturers. By so doing it will be possible to approach the operating requirements set down previously, and secure a breaker superior in performance to any now offered. Along with this must go continued research, looking toward the development of a device for the interruption of a high-voltage, a.-c. circuit which will be as dependable in its operation as is the transformer and generator. Pending this time, oil circuit breakers must be purchased and used with a full knowledge of their limitations.

## Discussion

**J. D. Hilliard:** In this paper the importance of high-speed switching in increasing the stability of the transmission network is emphasized, and the conclusion is drawn that the oil circuit breaker is the only piece of dependable apparatus at present obtainable, or likely to be obtainable in the near future which can be used for this work.

To this conclusion I think no exception will be taken by those familiar with the operation of interrupting devices for electric circuits, including the so-called vacuum switch.

For years it has been recognized that speed was one of the chief factors in the construction of an efficient oil circuit breaker, but it was also recognized that the oil breaker must be of sturdy construction. By speed I mean the total time elapsing between the beginning of the short circuit and the complete interruption of the current.

The fact that one breaker may have a shorter arcing period than another may be of small moment so far as system stability is concerned, if the total interrupting period of the two breakers is practically identical, and when test data are given both the total short-circuit duration and arcing duration should be given, if a logical comparison is to be made.

Whether a shorter arcing duration is favorable to one breaker as compared to another breaker will depend on the speed of break (per break unit) of the two breakers, and the number of breaks in series; in other words, it will depend upon the total quantity of gas generated in the two breakers.

Tests with plain-break contacts, operating under identical conditions, have shown that the two-break breaker is quite likely to generate less gas than 6, 8, or 10 breaks in series. It is a fact as the authors have pointed out, that a current-limiting resistance in series with the arc, greatly reduces the severity of the arc. This coupled with the light weight and high speed of the moving parts explains the superior action of small potential fuses where the current flow is limited by resistors. When, however, an attempt is made to apply the same kind of a device to an oil circuit breaker where the resistance must be shunted in circuit when the breaker operates, it is found that many difficulties arise, not the least important of which is keeping down the cost of the breaker equipment.

The authors have given the speed of a General Electric Company FHKO-36-33 C, 115-kv. oil circuit breaker as 5.5 ft. per sec. maximum at 300 amperes charging current. The interrupting capacity of this breaker for two O-C-O duty cycles is 3750 amperes at 115,000 volts, and since the speed of operation of this breaker is a constant of about 5 ft. per sec. at no load, plus a variable dependent upon the load interrupted, the figures given, although correct for the quoted load, are not half their real value when the breaker is interrupting its rated interrupting capacity.

Moreover, one can expect a longer arc when interrupting a small charging current than that obtained when interrupting the full interrupting capacity of the breaker, so that taking both these factors into consideration, one would expect the full-rating arc duration would be less than half as long as the charging-current arcing duration.

It is also a fact that the speed of operation of the explosion-chamber breaker is a maximum shortly after the end of the contact rod clears the throat bushing,—that is, the speed is a maximum at the time of the long arc, and this means the smallest quantity of gas during that period. This should be compared with the breakers having the maximum spring tension and maximum speed during the early stages of arcing when the gas generated per unit of arc length is small. In one case we have a maximum speed decreasing to a minimum; in the other case we have a minimum speed increasing to a maximum.

The quantity of gas generated at constant speed of contacts for a given arc duration varies approximately as the square of the speed, because the arc likewise varies directly as the speed.

When the above facts are considered, it is easily seen why the explosion-chamber breaker produces such a small quantity of gas, and why it has such a high interrupting capacity.

It is not clear to the writer why high speed of separation is necessary when interrupting line charging current or load currents of small magnitude, because under these conditions the line should be fairly stable.

For heavy short circuits, however, high speed would be advantageous, and it is under these conditions that the explosion-chamber breaker is at its best, and its strong construction enables it to stand repeated interruptions without damage.

The Canton tests were 26 and 30 consecutive operations on the two breakers, without examination of the oil or contacts, and both were in first-class condition at the end of the tests and could, undoubtedly, have duplicated the performance and still have been in good operating conditions. It is probable that 100 such operations would still have found them able to carry their rated load and interrupt their full rated interrupting capacity.

It is to be expected that the earlier explosion-chamber breakers would not be developed to the degree found in the modern breakers, that the years of operating experience would result in breaker improvements, that better constructional methods, better materials, and better workmanship would be built into the later breakers just as there have been improvements in the automobile in the same period.

It is unfortunate that the various curves mentioned in Messrs. Wilkins and Crellin's article are not available at this time, and, therefore, no comparison can be made on the time of relay action, breaker trip, and breaker interruption of circuit.

In the article no mention is made of tank pressures as a function of speed of interruption, and but little has been said concerning voltage rises due to the same cause.

Fairly high impact pressures must be expected in the oil when high-speed interruption takes place, although at the time there may be no evidence of pressure in the air space above the oil. This high impact pressure is due to the substantial incompressibility of the oil, the mass of the oil and the instantaneous generation of a gas in fairly large volume. It acts, of course, to stress the tank and unless the seams are well made, may result in their being opened up, whereas with a slower operating breaker the stresses may be considerably less.

The voltage rise, from substantially instantaneous interruption, is likely to be a real problem, and in such apparatus excessive voltages have been observed during tests, and the steep wave front makes it impossible to obtain an oscillographic record with the ordinary oscillographic apparatus.

Peak records can, of course, be obtained by a surge recorder, or by the cathode ray oscillograph, and such records have shown surges considerably in excess of any mentioned by the authors. It is not impossible that under special conditions, voltage surges of 25 times the applied volts may be observed.

The authors mention the fairly high power factor in a short circuit to ground. This is, of course, due to the ground resistance and was to have been expected. It also largely accounts for the fairly easy condition for ground interruption on a system having a grounded neutral. The fundamental requirements, as laid down by the authors, are not so impossible of achievement by the high-voltage oil circuit breaker as would appear at first glance, and with the exception of (1) *i. e.*, O-C-O cycle of operation = 0.2 second, can I believe be approximated if there is a demand for such a breaker and the purchaser is willing to pay the price of development.

The testing of oil circuit breakers by the manufacturer and user is of great importance, and the General Electric Company's engineers are not only making such tests daily at the factory, but have taken every opportunity to make tests upon operating systems.

The General Electric Company strongly recommends the publication of full detail information on such system tests. Such information will be of incalculable value to transmission companies and manufacturers of oil circuit breakers, and will act largely to dispel the skepticism concerning circuit-breaker operation and rating which now exists. The factory tests are considered of so great importance that a new testing generator has been constructed and will have been given preliminary tests by September 10, 1927.

This generator is the largest testing generator ever constructed, and is expected to give a short-circuit kv-a. of nearly 600,000. Space has been provided for additional generators of the same or larger capacity, and it is expected that if connected to the Mohawk-Hudson system ultimately a short circuit capacity of considerably in excess of 1,000,000 kv-a. will be available at both low and high voltages.

The testing installation has been made very complete, and comprises both resistors and reactors for current limitation, bomb-proofs in which to test the breakers, a separate oscillograph and assembly building and ample grounds surrounding the test plant, so that the test men and observers may be at a safe distance from the breakers tested to destruction, and every breaker which can be stressed to that extent will be so tested. The testing equipment will, of course, be as complete as it can be made, and instruments are provided for measuring all factors affecting the interrupting capacity of the breakers that it is possible to measure.

In the thousands of tests made with our factory testing generator during the past six years, we have observed phenomena far more severe than any ever recorded by us on tests made upon transmission systems. We have observed arc lengths in excess of the charging-current arc lengths observed by the authors; and it is my opinion that our testing conditions are more severe than obtained on any transmission system in existence today, if we except the operation of a transmission system at the instant of a lightning stroke.

These observed test values are used in the design of new breakers, and it is these observations which determine the physical dimensions of our breakers. It is because of our observations that the break distances of General Electric breakers are made consistently greater than those of any other manufacturer; and although we realize that it may be a rare occurrence for an arc to be drawn the full break distance, it is also realized that a sustained arc in an oil circuit breaker is a serious thing and may result in the destruction of the breaker, and must be guarded against at any cost.

The authors state that the manufacturers positively "refuse to give a guarantee on performance." I think that a consideration of the facts will show that statement is not exactly correct. While the General Electric Company does not guarantee their breaker rating, they do stand back of their breakers and will continue to do so.

At a joint meeting of the Oil Circuit Breaker Section of the Power Club and the Oil Circuit Breaker Subcommittee of the N. E. L. A. a year ago, all of those present were unanimously agreed that a manufacturer could not guarantee interrupting capacities of oil circuit breakers, because the interrupting capacity at any given instant depended on system, maintenance, and operating conditions which were entirely beyond the control of the manufacturer.

The Oil Circuit Breaker Subcommittee of the N. E. L. A., therefore, unanimously agreed that three alternative clauses be recommended to the manufacturers, but expressing a preference for the following clause:

"Because system, maintenance, and operating conditions are beyond the control of the manufacturer, interrupting capacities of oil circuit breakers cannot be guaranteed, but this does not relieve the manufacturer of his contract obligation to deliver oil circuit breakers having interrupting capacities as specified."

Acting on this recommendation of the Oil Circuit Breaker Subcommittee of the N. E. L. A., the General Electric Company adopted this clause as recommended. Under this clause, the company is bound by a legally enforceable contract to deliver a circuit breaker having the specified rating, and evidence that the circuit breaker does not have the rupturing capacity specified would force the company to replace the circuit breaker with one having the specified rating, or would make the company liable for damages for breach of contract.

There may be uncertainty in the minds of some manufacturers and some users as to the meaning of kv-a. interrupting capacity. Is it the interruption at unity power factor, or at approximately 90 deg. lag or lead? Is it the interruption of the current on an otherwise isolated bus system, or is it interruption on a system having a connected load with shunt reactance and electrostatic capacity? Is it on grounded or ungrounded systems?

As far as the General Electric Company is concerned, and based on engineering information that has become available from field and testing department experience, the General Electric Company's published interrupting rating includes all the conditions mentioned above and the General Electric Company will continue to publish ratings on this basis unless future development makes modification necessary, in which case, the published ratings will state that fact.

The writer regrets that the tests did not include repeated interrupting tests at or near the rating of the breaker so that observations of contact burning could have been made.

**H. E. Strang:** In discussing oil circuit breakers the term "Speed of Operation" is frequently used and unfortunately at times loosely applied with the net result that some confusion exists as to just what thought this expression is intended to convey.

From the standpoint of system stability, interest is centered around the total time required for opening a circuit from the instant the trip coil is energized until the arc is finally broken, rather than the actual speed in feet per second at which the contacts may part.

An analysis of the opening characteristics of various kinds of breakers will reveal the fact that one type of motor operator which imparts a comparatively high speed in terms of feet per second to the contacts after they have started moving, has an inherent time delay in the tripping mechanism itself, which makes the dead time, or the time from energizing the trip coil until the contacts part, nearly twice as long as in the case of breakers operated by other types of motor or solenoid mechanisms.

Supposing that there may be a balance in favor of the breaker operated by this former mechanism of some few half cycles of arcing time, the total duration of short circuit may be much longer than in the case of a breaker whose contacts travel more slowly, but operated by a mechanism with a shorter inherent dead time. It is this feature which is essential when considering the application of oil circuit breakers from the standpoint of their effect on system stability.

It is regretted that the curves which have been presented showing the opening characteristics of various types of breakers were not plotted on the same basis, that is, from the time the tripping impulse is delivered to the trip coil.

Figs. 9 and 10, showing the opening time of a General Electric FHKO-36-110-kv. breaker seem to answer a commonly raised question regarding the effectiveness of explosion chambers at low currents. In this case while opening only 300 amperes which is some 8 per cent of the breakers' interrupting rating, a definite acceleration is given to the contacts which amounts to an increase of about 2 ft. per sec. in maximum velocity over the no-load speed.

That this effect is consistent in reducing the arc length over the entire range of a breaker's rating is also apparent from the published results of the Canton tests where in the case of one explosion-chamber breaker during a series of 30 tests, ranging from 23 per cent and 83 per cent of its interrupting rating, the arc length varied from but 40 per cent to 20 per cent of the stroke.

As the authors have stated, the ultimate interrupting capacity of these large breakers may not be definitely known. It is believed, however, that if there is any uncertainty in the ratings it is on the side of conservatism, and that it is not necessary to apply factors of safety to the ratings of breakers which have been subjected to extensive factory tests, the results of which have been substantiated by field tests such as those made at Canton.

**M. M. Samuels:** May I be permitted to add some constructive suggestions? First is the question of the parts which the users and manufacturers should respectively take in the further development of breakers.

Now, it is not possible, nor is it necessary for an operating man to known as much about all of the detail problems of breaker construction as a manufacturer's engineer. But the operating man knows what he wants the breaker for, what service it has to perform, he knows this better than the manufacturer; he has to make it perform as part of a system, and he soon finds out wherein it fails so to perform.

Advice along these lines from operating men should be eagerly sought by manufacturers. The manufacturer should realize that the customer is not just kicking for the fun of it; but that when he kicks there is something wrong; and then let the experts get busy and find out what is wrong.

The needed spirit of cooperation on the part of the manufacturers is beginning to show itself here and there, and has no doubt been a contributing factor of considerable importance in the great strides which the manufacturers have made in very recent years in circuit breaker developments. But more of it is needed.

Another suggestion which may be made is that future tests should be carried on under actual operating conditions. So far, elaborate preparations have been made for each test. Contacts were cleaned and adjusted, mechanisms greased, relays cleaned, new oil placed in the tanks, etc. Under operating conditions this is not done every day, and in most cases it is not done often enough; and yet breakers have to operate.

I should suggest that in the future tests be made on breakers after they have been in service for some time, without making such preparations. In other words, without telling the breakers that they are going to be tested.

As to the concluding requirements of Messrs. Wilkins and Crellin, I may state that the one requiring a maximum of one kv. is to my mind not of great importance. I will grant that the great amount of power required to close some breakers is due to very clumsy mechanism designs. The bell-crank artist is still among us, and the manufacturers have not as yet learned that a good switch designer is not necessarily a good mechanism designer, and that none of the switch mechanisms shows the ingenuity and beauty which may be observed in some of the automatic machinery which they have in their own shops. However, give me a good breaker, and I do not care if it takes 5 kw. to close it.

The suggestion that it should be possible to install a breaker without skillful mechanics likewise seems to be going somewhat too far at the present. It is true that breaker mechanisms should be simplified rather than be made more complicated; but I doubt if it ever will be possible or even desirable to eliminate the skillful mechanic in the installation of breakers.

Let me add a concluding remark. It will be necessary to reduce the cost of breakers in the future. The breaker today represents the limit to electrical development, not only insofar as it sets a maximum to the amount of energy that can be safely switched, but also economically. Many a prospective development cannot be put through because the cost of switching makes the whole development uneconomical. It will not be sufficient in the future to spend half a million dollars on research to find out that the tank steel has to be ½ in. instead of ⅜ in. thick, and to spend another half million to find out that two more pounds of copper will have to be added to the contact, or that structural-steel tops are in some cases preferable to cast-steel tops. To our shame it must be admitted that the ratio of results to development expense is very low in the circuit-breaker field, and it is development expense which makes the cost of breakers so prohibitive.

Radical discoveries and inventions are needed, if the industry is to progress. A beginning has already been made, and one hint is already mentioned in the paper as to what might be expected in the future. I am referring to vacuum switching. But so far that is only a hint; and in general there are very few inventions of ingenuity and importance on record in the whole history of switching.

The industry seems to have been immunized against an attack by the bacillus of invention. Messrs. Wilkins and Crellin are right, therefore, in their statement that we are doomed to depend on oil breakers for a good long time to come; and that the improvement of them, to which I may add the reduction of their cost, is of immediate importance.

**L. C. Williams:** "Speed" is a much misinterpreted word. The electrical engineer talks in terms of cycles for interrupting a circuit or clearing a fault whereas the mechanician speaks in terms of velocities of the moving elements.

Let us consider switching time in two parts, (1) the time required to overcome inertia and acquire acceleration of blades and measured from the time the relay contacts close until the arcing tips separate and (2) from that point until the arc is broken and the fault cleared.

The sum of the two times is important from the standpoint of system stability and all operating engineers desire it cut to an absolute minimum.

The second consideration is of vital importance in switch performance as high blade velocities contribute to a short duration of arc and improvement in switch reliability.

Our present methods of control work somewhat at cross purposes. To gain high blade velocities is usually at the expense of burdensome control equipment and markedly increasing the time to get under way.

What we want is an improved control equipment which permits the switch to operate rapidly and minimize the overall operating time.

Slow-motion pictures taken of the mechanism of heavy duty switches emphasizes this necessity and likewise afford an accurate means of calibrating switch speed curves.

**W. S. Edsall:** The paper points out the desirability of clearing trouble from the transmission line in the shortest possible time. Several curves are given showing oil circuit breakers of the 110,000- and 220,000-volt class, giving the time required from closed position to the contact-breaking point and arc-clearing point. It is noted that on one 110,000-volt contact-break type of breaker it required about 0.125 sec., or 7½ cycles on a closed position to opening of the contacts. About 4½ to 5 cycles additional were required to break the arc of the changing current. Contrasted to this in a desire to point out that records are available showing the performance of the American Brown Boveri Electric Corporation BO-60, 110-D oil circuit breaker handling short circuit in the order of 400,000 kv-a. where the complete O-C-O cycle was made in approximately 14 cycles. This time is taken from the instant the contacts touched on closing plus the relay action time for reversal of motion of moving member springing the arc and complete interruption.

This type of oil circuit breaker is of the 10-break or multiple-break type. It is of the comparatively slow-speed design. In no case was the speed of the moving element higher than 2.8 ft. per sec.

The statement is made that records have been taken on 110-kv-a. oil circuit breakers both on 2-break and 6-break types, with speeds varying from 4 ft. per sec. to 15 ft. per sec. per contact and a range of arcing time from 12 cycles on the slow speed to 2 cycles on a higher speed. This would infer that the higher-speed breakers clear the arc more quickly than the slower-speed.

It is also stated that "the important point often overlooked is that the high-speed breaker clears the disturbance in much less time with much less damage both to system and to the breaker."

Records are available showing the type BO-60, 110-D, American Brown Boveri Electric Corporation oil circuit breaker, performing on O-C-O cycle with short circuit in the order of 500,000 kv-a. wherein it is shown that very slow speeds will interrupt the arc in the same time of arcing as with higher speeds. It was shown on one test that the average speed was approximately 5.5 ft. per sec. on opening and on the second O-C-O of the operating duty the speed was reduced to approximately 1.4 ft. per sec., approximately 50 per cent of normal, yet the time of arcing remained the same.

It is our belief that, contrary to the general thought, the introducing of greater speeds alone does not necessarily give better oil-circuit-breaker operation. It is our belief that the use of the 10-break multiple break with slow moving mechanical parts presents many advantages. Due to slow speeds there is no racking of mechanism at the end of the stroke, whether on closing or opening,—only simple torsional accelerating springs are used. There is no quick-break mechanism of any kind, hence no triggers, latches, nor springs.

Furthermore, it has also been demonstrated on tests that close to 700,000 kv-a. the use of the 10-break breaker gives pressures less than 20 lb. per sq. in. in the tank.

There have been some misconceptions as to the length of arc per arc and the total arc length in breakers of the 10-break type. It is true that if the speed of the moving element were the same in the 10-break type as in the usual 2-break type the total length of arc in the 10-break type might exceed that of the 2-break type. However, the speed of the BC-60 American Brown Boveri high-voltage oil circuit breaker is comparatively low, so that the total length of arc is very little if any greater than would be experienced on a 2-break type under the same conditions. It is definite that the length per arc is much less in each of the 10 arcs than the length of each arc in a 2-break type.

The paper makes a reference to the use of resistance in conjunction with one multiple-break oil circuit breaker. Reliable resistance-type multiple-break oil circuit breakers have been built in Europe for many years. Resistance is mounted within the tank at a point such as to clear it from precipitating carbon and low-dielectric oil at the bottom of the tank. The usual method is to connect resistance in shunt with 4 or 6 of the multiple breaks, leaving from 2 to 4 of the multiple breaks in series. Upon interruption the arcs which are shunted by the resistance are immediately made unstable, thereby leaving very high resistance in series with 2 to 4 arcs. This gives a high resistance against the recovering voltage, cuts down the current flow and acts to diminish the time of arcing. Breakers of the 110,000-volt class with interrupting rating of 500,000 kv-a. of the resistance type have been built and successfully operated for a number of years.

In summarizing we would point out that the high-voltage oil circuit breaker as manufactured by this corporation will probably come nearer meeting No. 1 requirement on the eighth page of the paper than any others on the market today. This requirement is that the complete O-C-O cycle shall not be more than 0.20 seconds. Interrupting-capacity tests in the order of 500,000 kv-a. show a time of 0.22 sec. average. The operating mechanism for these breakers is of the motor type, simple in construction and requiring very small current for operation. The power demand is less than 1 kw.

The breakers are of very simple construction, such as will enable them to go through many operating cycles with very little inspection.

**Philip Sporn:** (by letter) I am pleased that the authors have tackled a question that has not been given the attention it deserved, and that is the question of oil circuit breakers and their effect on continuity of service in transmission networks.

I think some work ought to be done also with particular reference to the effect on continuity of service of switching arrangements on high-voltage lines.

As a general rule a transmission line is planned and built by the transmission engineering department and when it is all over the job is given to the relay engineer to relay it. Sometimes he actually knows something about it a few months in advance of completion but it is very seldom he has much of a say in the arrangement of the line and the effect it will have on his various loop circuits. The fact that this additional line will make selective action almost impossible or, if it does make it possible, will introduce unusually high time settings on some of the lines, is not given very much weight and the problem is generally considered one of minor importance and one that a good relay engineer ought to be able to take care of. Of course where a double-circuit line between two points is involved, the problem is very very simple but very often the double-circuit lines do not materialize or where a line is laid out for two circuits, a single circuit only is installed and such a period may last for five years. The introduction of a pilot system of protection on transmission lines will materially ease the whole problem of sectionalization. It will particularly make possible the reduction in the time a fault is allowed to stay on the system and this will reduce to a negligible quantity not only the damage done during a fault but will also improve stability and will further reduce the trouble on customers' apparatus as a result of long surges on transmission systems.

Obviously if a carrier-current pilot system of protection is to be effective it has got to have a reliable means of coupling and Mr. Belt has shown[1] some of the devices that can be and are being employed today to obtain reliable and effective coupling. It is of course evident that there is no sense in making large expenditures on a relay system such as a carrier-current pilot system that will cut down relay action on a single line from 2 or 3 sec. to ½ sec. if the breaker itself will take an equal amount of time to function in clearing a short circuit after the relay system has energized its trip circuit and this point has been brought out very well by Messrs. Wilkins and Crellin. As an example of this, refer to Fig. 10 where one of the phases of a breaker is shown taking about 0.27 sec. before opening. Now, compared to a relay action of 3 sec. 0.27 seconds is quite good but when dealing with orders of time of relay action of about 0.5 sec. 0.27 isn't quite so good.

With some of the conclusions of the authors as to the fundamental requirements of a circuit breaker, I agree; with others I differ quite radically. For example, I believe that the operating time for a complete "Open-Close-Open" cycle of operations can be materially raised above 0.2 sec. provided the opening time can be reduced say to a figure approaching 0.05 sec., or, as an outside figure 0.1 sec. There is no question that the ideal half-cycle of arcing time would be a highly desirable thing if it could ever be obtained but I cannot quite see why it is necessary to limit the power demand of the mechanism to 1 kw. I do not see that it is necessary to have the breaker designed so that it can be installed, adjusted, and maintained by the average mechanic without oil-circuit-breaker technique. I should like to see them designed so that they can be installed, maintained, and adjusted and then stay put when worked on by the average mechanic who had some special training.

That it is highly desirable that a breaker shall be capable of completing more than two normal operating cycles before any inspections or adjustments are necessary, there is no room for argument. The wonder is that the present operating cycle was agreed upon and not rejected as utterly absurd by the operating people. I do not know whether 100 is at all essential but it ought to be of that order. For the present 40 or 50 would be good enough and I believe that if the operating engineers insist on it they will get it some day.

Again I am in entire agreement with the authors in that the only way for an operating company to know today as to whether the breakers that it is buying or that it contemplates buying will or will not perform satisfactorily, on its system, is to test them. Some day breaker development will have reached the point where this will not be necessary but it does seem necessary today. That this happy stage will arrive by combining all of the good features now available in the designs of the several manufacturers as the authors so confidently expect, I am not at all certain; we have seen in other lines of endeavor developments involving combinations of the best feature of each that gave a rather queer result. The problem would seem to be rather to have each manufacturer develop his design or new designs to a point where he is certain and doesn't merely think that the breaker will do what he says it will do.

**R. J. C. Wood:** One of the oscillograms shows the current increasing on interrupting the charging current on the line. Mr. Crellin said this was contrary to the ordinary conduct of current on short circuit.

In testing Mr. Sorensen's vacuum switch, which was done by bringing a synchronous condenser up to speed on the system, disconnecting from the system, and throwing it on the switch and using it as generator, we had occasion to notice the shape of the short-circuit current during the time previous to the opening of the switch. Quite a number of oscillograms of short-circuit current were made, some of them showing the ordinary asymmetrical type but quite as many showed the short-circuit current increasing for the first few cycles.

**E. A. Crellin:** It was short-circuit current.

**R. J. C. Wood:** But a single-phase ground.

**F. C. Lindvall:** The authors mention the possibilities of the vacuum switch. We at the California Institute of Technology who have worked on the problem of breaking currents in vacua are quite gratified by this recognition, for not all operating engineers and oil-switch designers are convinced that some day the vacuum switch may be a reliable piece of station equipment.

We feel that our optimism regarding the switch is justified, and that the fundamental idea of the switch is sound. Yet, as Mr. Crellin pointed out, the transition from a rather delicate piece of laboratory equipment to a reliable device for commercial service is a long step which presents numerous difficult technical problems; but fortunately, as more new work is done on the switch, many anticipated difficulties eliminate themselves.

Two such points that the authors mentioned in their paper should be discussed briefly. First, we have found that the extremely high vacuum which was originally assumed to be an obvious prerequisite is not really necessary. This interesting fact was observed in a general way in the earlier vacuum switches, but in order to obtain more definite data on this point a small switch was constructed. This model had butt contacts of ½-in. aluminum rod. An ionization gage located between the switch and the cut-off from the diffusion pumps served for measurement of gas pressure in the switch.

For convenience in testing, the duty cycle of this model consisted of short circuiting and immediately opening the short-circuit on the high side of a 15,000/220-volt 10-kv-a. transformer. The short-circuit current through the switch was 3.5 amperes and the potential across the switch after break was of course 15,000 volts. For the first 20 or 25 trials of the switch at a pressure of $2 \times 10^{-5}$ mm. of mercury severe arcing resulted with consequent liberation of gas from the electrodes. However, the contacts were then in shape for proper switching and successful operation followed. In fact, at a vacuum of the order mentioned, an arc could not be drawn out to maintain between the contacts even with maliciously slow operation.

Several runs of 400 or 500 operations were made with the switch cut off the pumps with careful note taken of time and of changes in the vacuum. These pressure changes were then compared with leakage curves taken on the switch, and the interesting result was that the rise in gas pressure during the long switching runs followed very closely the curves of leakage coming from a faulty seal. In other words, the amount of gas given out by switching with clean electrodes was but little.

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[1] *Coupling Capacitors for Carrier-Current Communication*, T. A. E. Belt, A. I. E. E. JOURNAL, October, 1927, p. 1051.

The switch functioned consistently and was apparently indifferent to existing gas pressures up to the order of $5 \times 10^{-3}$ mm. Beginning at somewhat lower pressures decided flashing could be seen at each operation of the switch, but every time a successful break was made. As a matter of fact, the switch would break current satisfactorily with sufficient gas present to give a solid negative glow from a spark coil through a side discharge tube. Hence, to generalize from these results it follows that with outgassed contacts only a tolerably good vacuum, one which is relatively easy to get and easy to maintain, is needed for successful switching. Thus, at once, many of the troublesome details of high-vacuum technic are avoided, and in consequence the switch lends itself more readily to the ordinary methods of manufacture.

The second point mentioned by Mr. Wilkins and Mr. Crellin, that of operating the contacts within the vacuum chamber, has been simply and adequately solved through the use of flexible bellows, which makes possible moving the switch contacts through any required distance by any suitable mechanism. As a consequence the switch may be locked in closed or open position, a feature demanded by the operating engineer.

We have also found that extreme speed of opening is unnecessary in the vacuum type of breaker. Thus the contacts themselves may be simple and have low inertia. In turn, the operating mechanism may be of light construction, permitting the operating speed of the switch as a whole to be made extremely high. This speed, together with the characteristic first half-cycle break of current, will give a circuit breaker whose operation will no doubt be rapid enough to meet modern switching requirements.

A further desirable feature would follow in that the simplicity of the operating mechanism of a vacuum switch should allow an accuracy of adjustment which would result in more nearly approximating the simultaneous breaking of current in the three phases of the switch.

**R. W. Sorensen:** Reference has been made to the development of gas pressure tending to rupture switch tanks when a switch is open, and the question has been asked, does this phenomenon of pressure occur in the experimental vacuum switches when such switches fail to function properly and do not interrupt the current? It would be natural to expect in case of failure to interrupt the circuit that gases might be given off from the switch terminals in sufficient quantity to develop pressures that would cause an explosion or bursting of the chamber containing the vacuum switch. Experiments which have been made with the vacuum switch in which over 150,000 kv-a., single-phase has been interrupted by means of single-pole switches have failed to show enough gas pressure to produce explosion. Also, when circuits of this capacity have not been completely interrupted by the opening of the switch, the switch has withstood any tendency toward an explosion. In a few cases where the glass container for the vacuum chamber has broken, whether due to heat or mechanical injury, the parts of the glass container have not been thrown about so as to indicate an explosion, but have rather simply dropped to the ground and done no damage; in fact, we have had less flying of glass than is often the case when an ordinary electric light globe is broken. As an indication of our confidence that no explosions occur, I may say that those of us who are working with switching in vacuum have so little fear of flying glass or other parts that we stand within a few feet of the switch in order to watch its operation when experiments are being conducted; in fact, we approach the switch much closer than has been considered safe with oil switches which may throw oil.

Another very favorable feature of the vacuum switch is the low voltage rise in the circuit at the time of break. For, though the vacuum switch always breaks the circuit on the first half cycle, we have found the voltage rise with the vacuum switch to be less than with the oil switch. The oil switches we have worked with usually hold the arc 8 or 10 half cycles. That is, there seems to be more rise in voltage on the circuit at interruption when it takes several cycles to make the interruption than there is when interruption is made during the first half cycle. Many times in our laboratory we have put one of our vacuum switches in a convenient 15,000-volt circuit capable of supplying current up to 150 amperes and have, by means of the hand-operating lever, opened and closed the switch rapidly, perhaps six or eight times per second. This we can do 25 or 30 times without distressing the switch in any way. I have never seen such a demonstration made with an oil switch. In fact, the amount of energy expended in the switch does not seem to be great, the actual drop across the arc at separation of contacts being probably less than 100 volts. This means that there is not available a great deal of energy at the place where it will destroy switch contacts. One of our small switches, the contacts for which are rods ⅜ in. in diameter, has been used to open a 15,000-volt circuit, the current in which varies from a small amount to 125 amperes, more than 4000 times and the contacts show no appreciable pitting. I feel that we may safely say, therefore, that a vacuum switch which has been properly tuned up for operation will give good service and be able to interrupt circuits almost an infinite number of times without damage to contacts.

I do not wish in any way to give an impression that vacuum switches are ready for the market. During the five years we have been working on the switch we seem to have made small progress. Each move, however, has been a progressive one and perhaps it will not take five years more to develop a switch which will have some degree of success in practical service on power lines.

In conclusion, I can reply to Messrs. Wilkins and Crellin by saying that we have developed a means for moving practical circuits in a satisfactory way. We have also been able in an experimental way to fulfil requirements 1, 2, 3, and 4 as listed in their paper. Requirement No. 5 is the one we have not as yet been able to meet.

**E. K. Sadler:** We have just completed some over-all tests, at our factory, which approach Messrs. Wilkins and Crellin's specifications; and I should like to make a few remarks on that.

We have found it possible to obtain the following speeds without complicating the operating mechanism or subjecting the switch to excessive jar in operation. This switch was of the six-break type and the speeds given are the total for all six breaks.

We have obtained a velocity of 51 ft. per sec. when the arcing contacts break and a maximum velocity of 75 ft. per sec. at a point some inches beyond where arcing contacts break. Opening of switch requires only 0.089 sec. for full travel of blades, and an elapsed time of 0.16 sec. from energizing the trip circuit until the arcing contacts open. The total break equals 36 in.

As regards a switch jumping when the operating mechanism is mounted remote from the switch; this switch can move 2 in., back, forward, right, left, up or down and still operate perfectly.

**J. P. Jollyman:** From the standpoint of the engineer having to do with the operation of a power system, we are very much concerned with the effects of trouble on the power system. We want to get those troubles off the system as quickly as possible. We do not want to wait until the voltage of the system is reduced to a point where the duty on the circuit breaker is reduced. We want the trouble removed before service is impaired and whatever kind of switch it is will have to stand this quick service.

**J. S. Thompson:** (communicated after adjournment) It is of incalculable value to the manufacturer of oil circuit breakers to secure the findings of engineers who have so thoroughly studied the problems to be met in oil-circuit-breaker design and to have the result of these studies summarized in the requirements which they have laid down. These requirements are looked upon as supplementary to most of those outlined by Mr. Jenks of the West Penn Power Company, in the paper appearing in the 1924 TRANSACTIONS of the A. I. E. E., p. 648.

With reference to requirement 3, it is possible that a statement that the mechanism should demand but a very small amount of power would be sufficient, but the exact reference to 1 kw. is presumably prompted by the fact that mechanisms are available which require no more power than 1 kw.

With regard to the discussion presented by Mr. Sporn, it would appear that his reference to the absurdity of the test duty cycle demand is based upon a tendency to look upon test rating as synonymous with normal operating ratings in circuit-breaker practise. In all other apparatus the test ratings to which the apparatus is submitted, for periods such as one minute, are far in excess of the operating rating and therefore it is possible that some adjustment should be made so that the circuit breaker operating twice under the A. I. E. E. test rating would operate comfortably at a reduced operating rating for the 100 or even the 1000 operating cycles referred to in requirement No. 4. We would draw attention to the fact that the N. E. M. A. rule for reduced interrupting capacities, under item E, suggests the ratio which these two ratings might bear to each other.

With regard to the discussion presented by Mr. Hilliard, the uncertainty regarding circuit breakers on the part of those best informed is indicated by the phrases: "It is quite likely"; "Not half"; "One may expect"; "It is probable"; "Could undoubtedly"; "May result"; "Is likely to be"; "It is not impossible."

Mr. Hilliard appears to assume that doubling the speed of the break would invariably double the length of the arc, and with respect to this assumption, we would draw attention to Figs. 4 and 10, showing arc durations of two-break and six-break circuit breakers under exactly similar conditions. These curves indicate a duration of arc of 0.045 sec. in the six-break circuit breaker and 0.15 sec. in the two-break circuit breaker.

There would appear to be an inconsistency in Mr. Hilliard's reasoning where he suggests that a greater quantity of gas is developed by high contact speed, whereas later in his discussion he states that high speeds are advantageous.

Mr. Hilliard indicates that high-speed interruption produces voltage surges and also impact pressures in the oil. If this is the case it would appear that voltage surges are a necessary concomitant of high-speed circuit interruption. But regarding tank pressure, it may be stated in support of multiple breaks that no Pacific Electric Manufacturing Company six-break oil circuit breaker tank or top casting has ever been damaged either under test or operating conditions, nor have tank and cover assemblies ever been forced apart.

Mr. Hilliard makes the point that the long break is of value and, recognizing this, the Pacific Electric Manufacturing Company provides that each one of the six breaks of its circuit breakers is substantially as long as each one of the breaks of the conventional two-break oil circuit breaker. Properly disposed multiple breaks can be considered as a grouping of two-break oil circuit breakers in series, and could not be assumed to draw arcs, per pair of breaks, as long as a single two-break oil circuit breaker. This fact has been put in practical application on a Pacific Coast operating system on which the failure of a two-break circuit breaker was remedied by placing a similar two-break circuit breaker in series with it, the two mechanically connected to operate simultaneously. But a further advantage of six-break circuit breakers is obtained by so disposing the breaks that the explosive effect of one arc tends to blast a volume of oil through the path of adjacent arcs.

With regard to the comment submitted by Mr. Strang, the factor of inherent time delay in the tripping mechanism is a vital one. In developing the motor-wound spring-operated mechanism devised by Mr. Wilkins, the engineers of the Pacific Electric Manufacturing Company gave this factor prime consideration, with the result that the inherent time delay in this control is satisfactorily brief. It is possible that the control referred to by Mr. Strang could be corrected to secure equally excellent characteristics.

**E. A. Crellin:** Everybody seems to have remarked about the power demand of the operator being limited to one kw. Mr. Samuel says, "Give me a good breaker and I do not care if it takes five kw. to close it." It is granted that it makes little difference to the switch itself how much power it takes to operate it so long as there is sufficient to get the contacts in or out in fast time. The limitation was added for another purpose and was included along with the other specifications to complete the list of requirements.

Let me point out what is involved in a large operator power requirement, especially in a breaker which requires practically the same energy to open as to close. I recently visited a substation in which there will ultimately be some fifty 60-kv. breakers and six or eight 220-kv. breakers, the most remote of which are 900 or 1000 ft. from the switchboard. If it is necessary to have operating currents on the order of 200 amperes at 125 volts, we are faced with a very great expense in storage batteries and control cables in order to hold up the operating voltage. It may well happen that a group of breakers will be simultaneously tripped, and if they require heavy operating currents to open, will force the installation of expensive equipment. Even with the gravity-opened breakers, it may well be that a large series of successive operations will lower the battery voltage to a point where further operation is impossible. The reason for imposing the limitation on operating power was to effect economies in installation. Such operators are available, and greatly to be preferred to those requiring 200 or more amperes.

Mr. Williams and Mr. Strang both have the same thought on the definition of speed. It is high over-all speed until the circuit is cleared that we are after. If the actual time of contact movement is kept relatively high for reasons of switch design, then speed must be attained in the operating mechanism in order to bring down the total time from the closing of the relay contacts to the final interruption of the circuit. In this paper "speed" does not mean the rapid motion of parts so much as it does the rapid interruption of the circuit, no matter how attained. It is felt by the authors, however, that much higher contact speeds than those at present obtaining will be of great advantage not only in preserving system stability, but in easing the stresses within the breaker itself.

**Roy Wilkins:** Mr. Hilliard states that "for years it has been known that speed was one of the chief factors of an efficient oil circuit breaker." Nothing seems to have been done about it, however, until very lately.

With regard to the testing of breakers below their rating, it might be well to point out that most of the failures on operating tests including those at Canton have been very much below the breaker ratings.

Mention was made of the fact that substantially instantaneous interruption causes very great voltage rises. This was the original argument against oil circuit breakers and is as true today as it was in 1895. There are as yet, however, no commercial oil circuit breakers that even approximate instantaneous interruption. No one has any hope of getting under the first half cycle. Mr. Sorensen has noted no alarming voltage rise at one-half cycle. In this connection, as was pointed out in the paper, the circuit characteristics are the determining factor on such phenomena.

With regard to guarantees, there were last year in one State of the U. S. some twenty times as many law suits for damage due to defective transformers as there were due to oil circuit breakers; the same arguments hold for both as far as care and maintenance are concerned, yet no reliable manufacturer proposes to withdraw the transformer guarantee.

With regard to the meaning of interrupting capacity in kv-a., I am frank to state that I, for one, am doubtful of what it means, if anything. Several years of intensive study in both the field and factory have so far only strengthened this doubt.

Multiplying a voltage on the bus before trouble by the current in the first one-half cycle of arc after trouble has no physical meaning and so far as yet demonstrated no practical one.

With Mr. Strang we are in thorough accord; it is a performance that is desired. The particular mechanism required may in the end not even remotely resemble any of the present types. The effect of trouble on the system is important, the effect on the breaker incidental, though all too often it is the controlling factor.

In reply to Mr. Edsall, I wish to emphasize again that what the purchaser buys is equipment to separate an operating system from a fault,—the fault and the oil circuit breaker condition at the time are secondary matters. While slow speed may be good for the breaker it decidedly is not for the system.

Breakers must be built whose opening time is under 0.1 sec. preferably as low as 0.05 sec. and whose arcing time approaches closely the optimum of ½ cycle.

Executives have been busy in the past with other matters, but of late they are giving more and more time to interconnection and network operation and the effect of combinations of networks. Eventually they will learn that the reliability of the entire network depends on the ability of the circuit-interrupting equipment to function properly in less than the time required for the parts of the network to pull out of synchronism and such circuit-interrupting equipment will then be demanded and made.

The point and purpose of the paper is not an attempt to design an ideal circuit breaker but to outline the requirements.

There are at present two theories or methods of network operation,—one with relatively light ties in an extensive network where each load is fed from more than one source, and in trouble, the smallest practicable section is isolated. Such systems require fast relaying and insure continuous service and are represented by the Pacific Coast, the Southeastern and the North Central networks in the United States, all covering extensive territories.

The second method depends on a backbone with radiating feeders where large blocks of power are transferred from the general source to the loads and where outages are not expected on the main arteries. Such systems provide only emergency relaying on these main lines because their loss means the serious crippling of the system, and extremely fast operation would not be necessary. No such system exists today in practise on anything like the scale of the type given above.

# Lightning Protection for Oil Storage Tanks and Reservoirs

BY ROYAL W. SORENSEN* JAMES HUGH HAMILTON† CLAUDE D. HAYWARD‡
Fellow, A. I. E. E. Non-Member Non-Member

***Synopsis.***—*This paper outlines work done in connection with planning a protection scheme for the oil storage tank farms of the General Petroleum Corporation of California. The work shows that the average annual number of storms at a given location is a constant. The dielectric property of oil has no influence in causing lightning or inducing it to strike oil in storage.*

*Tests show that excellent protection can be obtained by towers properly installed, but they do not indicate absolute immunity against hits.*

*The work done also shows that an extensive field program, supplemented by such laboratory work as required for understanding and assisting the field program, should be carried out to extend our knowledge of lightning phenomena and protection.*

* * * * *

## INTRODUCTION

In California, the production of great quantities of oil has made necessary the development of storage capacity for millions of barrels of oil of varying degrees of inflammability.

Three types of storage containers have been used; all steel tanks, tanks with steel walls and roofs of some other material, and large concrete basin-like structures commonly known as reservoirs.

Previous to 1926, on California oil properties, fires resulting from lightning were scattered as to time and place. Also, insurance rates for damage to these properties by lightning were sufficiently reasonable to make such insurance more economical than the employment of protective measures for oil or oil products against induced and direct-hit ignition by lightning.

Three major fires which occurred during April 1926, resulting in the loss of several lives and almost $20,000,000 worth of property, immediately caused a large increase in insurance rates and entirely changed the aspect of the problem in emphasizing the fact that insurance can never compensate for the economic loss involved in the destruction of large quantities of oil.

The average number of thunderstorm days per year for a given geographical location is, according to Weather Bureau statistics, a constant which has not changed during the period covered by their records (Fig. 1).

In different parts of the United States, the number of such days varies from less than 5 to 95 per year. Small areas within the divisions represented by the reports may have a greater or less number of such days.

The probability of damage by lightning in any given area is largely a function of the number of storms occurring within that area, the amount of the area occupied by life and property, the character of structures or materials included therein, and the absolute humidity—which determines the percentage of lightning discharges that will occur as strokes to ground.

Each year adds to the portion of any given region occupied by life and property and increases accordingly the probability of loss of life and damage to property. For this reason, not only the petroleum industry but also other industries should consider means of protection for the future in addition to those required at present, and should make it possible for engineers and scientists to plan and execute a thorough program of field researches on the character of lightning discharges, supplemented by such laboratory work as may be required for the development of the apparatus for these tests and interpretation of the results obtained in the field.

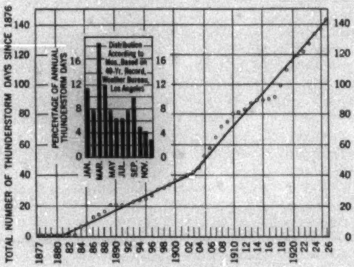

FIG. 1—NUMBER OF THUNDERSTORM DAYS IN LOS ANGELES SINCE 1876

Cumulative chart from records of the Weather Bureau. In this form a straight line indicates a constant thunderstorm frequency. It should be noted that in 1903, an alteration was made in station regulations equivalent to changing the official definition of a thunderstorm from "thunder with rain" to "thunder with or without rain." This explains the increase in thunderstorms recorded since 1903. (From Marion E. Dice, "Lightning Hazards," *Oil Bulletin*, 13, 27, Jan. 1927.)

Directly following the 1926 oil fires, several oil companies using the laboratories at the California Institute of Technology as a base, independently or in cooperation with members of the Institute staff, undertook the problem of designing protection for their oil storage properties. The most extensive of these programs was conducted for the General Petroleum Corporation by Marion E. Dice of their Consulting Engineer's Depart-

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ment and the California Institute of Technology High-Voltage Laboratory staff. It forms the basis of this paper.

### EFFECT OF LOCATION ON LIGHTNING HAZARD

Given a geographical section within which certain industrial operations are to be carried on, are there spots within that area which vary as to the probability of a lightning discharge?

A study of contributing causes for lightning, such as the breaking of water drops in upward currents of air[1] at the required velocity, showed that much can be done in reducing the lightning hazard by proper location with respect to thunderstorm paths.

Lightning damage may be caused by direct stroke or by ignition from secondary or induced discharges. As the energy in discharges caused by induced charges is relatively small, oil fires from this means can result only by such discharge acting as ignition systems. The obvious method for guarding against such effects is to reduce to a minimum the storage of highly combustible oils or gases given off by oils, and to keep well guarded against spark discharges the oils that are the more highly inflammable or give off gases which, with air, form explosive mixtures.

The well-known impossibility of producing differences of potential between two objects within a completely closed conducting envelope by influences exerted without the envelope indicates the proper solution for the problem of induced discharges. In practise, therefore, the desired protection from induced effects has been obtained by storing readily inflammable oils or oils which will give off explosive gases in all metal tanks, with well screened and properly designed vents or by the use of wire networks over wooden roofs. Floating roof construction, which reduces to a minimum the free gas space above oil in a tank, is an aid to this form of conservation. Tanks constructed in this way are costly and it is therefore not practicable to use them as general storage for the millions of barrels of oil now stored. Fortunately a great percentage of the oil can be reduced to a heavy residuum of low volatility for storage. This heavy residuum can be safely stored in the large reinforced concrete reservoirs, used so extensively in California, or in metal tanks with non-metal, non-floating roofing, providing such reservoirs or tanks are protected from direct hits.

Before discussing methods of guarding against direct hits, the authors wish to present some data bearing upon the possibility of any special phenomena related to lightning which may be directly chargeable to the influence of the oil itself.

### COLLECTION OF CHARGES ON OIL SURFACES

It was suspected at one time that certain oil fires of unaccountable origin might have been due to ignition from sparks caused by independent charges accumulating on parts of a large oil surface and then coming near enough to each other to have their charges equalized by a spark between them. The apparatus shown in Fig. 2 was used to make tests relating to this possibility. With voltage applied to the pan and terminal above it as electrodes, charges could be detected at the surface of the oil only while such voltage was applied. Also, during the application of voltage, the oil was always in circulation, the rapidity of circulation being a function of the potential gradient through the oil. Bits of cork or other insulating material in the oil would show a rather definite circulation path from the strong field under the rod above the pan out to the weaker field. Frequently particles of insulation material in the oil, because of some pecularity of shape or color, could be singled out and watched. Many of these particles were seen to act as though they were in the business of carrying charges from the surface of the oil to the pan at the bottom; that is, with a rate of motion entirely apart from the rate of circulation of oil, these particles would come to the oil surface, move down until they touched the pan at the bottom, and then come to the surface again to repeat the operation. As a further check, a charged electroscope was connected to a conductor which was allowed to touch the surface of the oil. In every case the electroscope was very quickly discharged. Also, it was found that the electroscope could not be charged above the potential drop through the oil so long as it was kept connected to the surface of the oil. These tests showed, as did similar earlier[2] ones, that oil cannot accumulate charges at points on its surface. Thus, there need be no fear of isolated or local charges on the surface of oil building up or approaching each other, and igniting the gas above the oil by spark discharges.

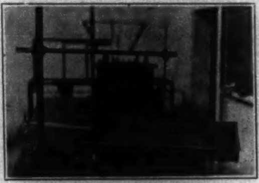

FIG. 2

### INFLUENCE OF OIL ON SPARK DISCHARGE

In planning protection for oil storage, one is confronted with the question; does oil have to be considered as a special problem because of characteristics which have influence, different from those of other substances, in directing the path of a lightning discharge between a charged cloud and the earth, or because of any special phenomena relating to the accumulation of charges on the surface of a body of oil.

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[1] For all references see Bibliography.

[2] Loc. cit.

It is a known fact that when a high potential direct current is applied to two electrodes insulated from each other, a dielectric, such as glass or mica, placed near the positive one materially lowers the voltage required to give arc-over between the two terminals.[3] At the suggestion of E. R. Wolcott of the Union Oil Company of California, oil, being a dielectric, was examined for such an effect with negative results. There was found no evidence that spark-over voltage between two charged electrodes was changed by placing oil on the positive one. This is fortunate, for if oil in a reservoir on the ground could act to lower the discharge voltages, there would be a great hazard for the oil, whenever a negative cloud formed in the region of storage.

This absence of any influence of the oil to cause it to be a more probable target for spark discharges was also checked by the use of the piece of apparatus shown in Fig. 2. This apparatus consisted simply of a large shallow pan partly filled with oil. With an electrode above the pan (as shown), connected to one terminal of the source of direct current supply and the pan connected to the other many tests were made. These tests show that as the voltage was increased, the oil was agitated more and more violently until, as the voltage approached that required for arc-over, the oil was hollowed out under the upper electrode, as though blown away, and when the depth of oil directly under the electrode was sufficiently small, the arc struck through the oil to the pan. If the voltage was kept constant and the oil level in the pan raised by adding more oil, the depth of oil (or, in other words, the thickness of insulation over the pan), was increased, and no arc from upper electrode to pan took place. Also, when the oil film was not punctured, there was no arc discharge from the upper electrode, the discharge around this electrode being limited to the corona discharge; that is, an arc does not strike from a conductor to an insulator unless the potential gradient over the insulator is great enough to either puncture the insulator or carry the arc around it through the medium surrounding the insulator. This is a fact of which one sometimes loses sight in thinking of the action of two insulators having different dielectric constants when placed in series in an electric field. When voltage is applied to such an arrangement, while it is true that the greater stress is upon the insulator with the smaller dielectric constant, it is also true that in order to obtain an arc there must be complete breakdown of both dielectrics by puncture or arc-over, as the arc cannot strike through one dielectric to the other as a terminal.

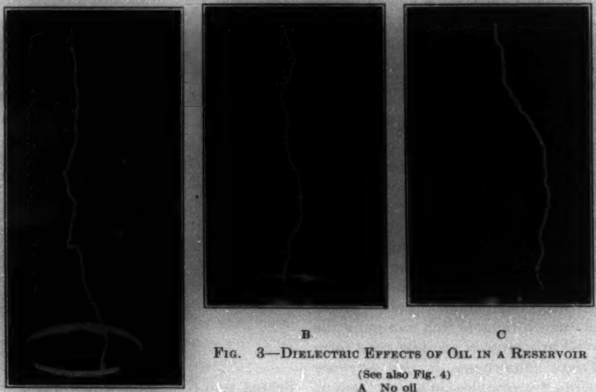
A B C

FIG. 3—DIELECTRIC EFFECTS OF OIL IN A RESERVOIR

(See also Fig. 4)
A No oil
B No oil
C Oil in reservoir

As a further check upon the inability of oil in a vessel to cause the discharge to take place more readily, many tests were made with smaller pans, dimensions of which were proportional to those of reservoirs. These were placed on the floor below the electrode used to represent a cloud, the other terminal of the power supply being grounded to the floor. With oil in the pan, the discharges missed the pan altogether or struck the edge; without oil in the pan, the discharges would hit in the pan or at the edge indiscriminately as shown by Figs. 3 and 4.

## LIGHTNING STROKES

There are three possible ways of guarding against direct hits; *viz.*, to prevent the occurrence of lightning discharges between clouds and earth, to construct the tanks or reservoirs in such a way as to provide immunity to damage from such hits, or to direct the hits elsewhere to conductors which will harmlessly carry a discharge occurring between cloud and earth until all energy of the discharge is dissipated. All of these suggested solutions were discussed shortly after Franklin's invention of the lightning rod in 1752, were revived and again thrashed out about 100 years later when Sir W. Snow Harris devised lightning conductors for ships of the English Navy, and more than 50 years since were reduced to scientific analysis by Sir Oliver Lodge.

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[3] Loc. cit.

To prevent lightning discharges between clouds and earth, it is necessary to provide a means of preventing the accumulation of sufficient charge on cloud and earth to cause a discharge to take place between them. There are no known records of this having been accomplished in such a way as to make available any data on energy discharge from structures erected for this purpose, though there have been many schemes suggested[4]. These schemes rely for the most part upon the use of points attached to earth as a means of discharging the charges produced. Tests to determine the value of such a scheme should be made on actual tower and point installations in a district subject to many lightning storms. Not having available such an equipment, tests were made with laboratory apparatus as shown in Fig. 5. This apparatus was constructed to scale and tests made for several conditions involving different actual dimensions.

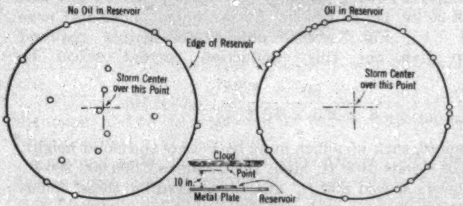

FIG. 4—DIELECTRIC EFFECT OF OIL IN A RESERVOIR WITH GROUNDED WALLS

These records show that the presence of oil in a reinforced concrete or metal reservoir tends to direct electrical discharges, which would otherwise strike into the body of the reservoir, to the edge. At the same time, the presence of a body of oil of the proportions of a reservoir in a thunderstorm field does not affect the number of discharges which fall within that area. Oil does not attract or repel lightning. In the tests, discharges from the surge generator were directed into a scale model of one of the 500,000-bbl. Wilmington reservoirs when empty and when full of oil (13 deg. residuum). The storm center was over the center of the reservoir at an elevation of 1000-ft. (actually 10-in.). The small circles show the location of hits.

| | Results | |
|---|---|---|
| Point Struck | Reservoir Empty | Reservoir full of Oil |
| Edge.......... | 8 | 17 |
| Inside......... | 8 | 0 |
| Outside........ | 4 | 3 |
| | 20 | 20 |

In these laboratory tests, steady unidirectional fields were used, because, had alternating fields been used, the total current measured would be the resultant of an energy current in phase with the voltage and the charging current leading the voltage 90 degrees. Lack of a proper wattmeter for use under such small current, high-voltage conditions would make the separation of these components very difficult. There are also other difficulties with alternating fields, such as distorted waves having greater peak value on the positive half cycle than on the negative half cycle, which make the separation of energy current from total current practically impossible. With direct current, these complications are avoided and the conduction current between points and the upper plate has a steady value for any given voltage.

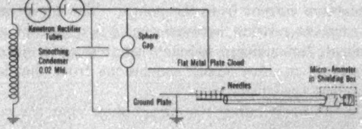

FIG. 5—DIAGRAM OF TESTS ON DISSIPATION OF ELECTRIC CHARGE BY NEEDLE POINTS

The apparatus (Fig. 5) consisted of two parallel flat metal plates, mounted horizontally and insulated from each other. The upper plate represented the thunder cloud and by means of the kenotron and condenser equipment shown in the figure, could be charged to a maximum potential of 100 kv. The lower plate was connected to ground and represented the earth surface under the thunder cloud. A number of steel needles, (Fig. 6), projected through holes in the grounded plate. Each needle was insulated from the plate by means of a small piece of glass tubing and all the needles were connected together at their lower ends by a third, smaller, flat metal plate which in turn was connected to ground through a micro-ammeter. The connecting lead was carefully shielded against induced charges by a grounded metal tube which surrounded it, and the micro-ammeter itself was placed inside a grounded screen wire cage.

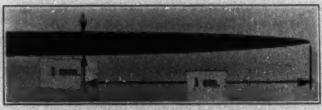

FIG. 6—DIMENSIONS OF NEEDLES USED IN FIG. 5

For each set of readings, the upper plate was set at a

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4. Loc. cit.

given distance above the lower one, the points were raised above this plate 1/12 the distance between plates, and the needles were separated a distance of four times the needle height. The sphere-gap was set for a desired value and voltage was applied, slowly increasing until the gap sparked over, at which time the micro-ammeter was read.

Results of some of the tests made are shown in Fig. 7. Each curve demonstrates the relation between the average voltage gradient between the plates and the conduction current from the points. The curves give no constant relation between conduction current and gradient, but indicate so many variables as to make it impossible to draw many conclusions from the data at present available.

On the other hand, the curves show that the conduction current is practically zero (less than $10^{-8}$ amperes) up to a certain critical gradient in each case. From this point, as the gradient is increased, points are obtained according to some regular law (which permits them to be plotted as points in a curve). They also show that the current is influenced by the actual size of the apparatus within the range available in the laboratory at the present time, but it is inconceivable that the same order of increase of current with increase of scale will be maintained up to the scale of clouds and lightning towers in actual use.

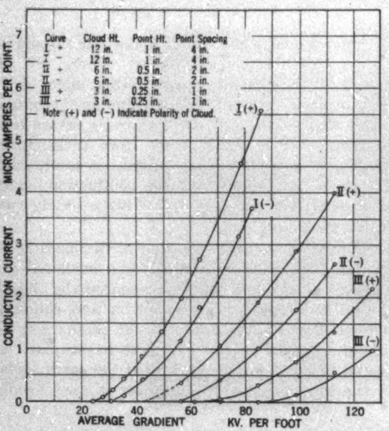

FIG. 7—DISSIPATION CURRENTS OF NEEDLE POINTS DISCHARGING AN ARTIFICIAL CLOUD

If conduction current great enough could be obtained, there would be a possibility of keeping the potential between earth and clouds down to a value too low for the discharge by lightning. Some calculations based on the data obtained from the tests just described, and from other investigations, may be of interest in this connection.

C. T. R. Wilson[5] shows that a probable charge of 50 coulombs is neutralized by a lightning flash. Simpson[6] states the total charge to be of the order of 100 coulombs. Norinder[7] found the time required for building up charges preceding lightning flashes to vary between large limits, the short intervals being only about three or four seconds and the longer ones, several minutes. Apparently a large number of them are built up in 10 sec. or less. Assuming for our calculations, a time of 10 sec. allowed for the accumulation of a charge of 50 coulombs, resulting in a gradient of 100 kv. per ft., if it is assumed that the gradient builds up at a uniform rate during 10 sec. of applied voltage the average current would be approximately 2.5 microamperes flowing for eight seconds, if it takes a gradient of 20 kv. per ft. to start the current as shown by Curve *I* (+), Fig. 7. The number of points required to give out this conduction current would be

$$\frac{50}{8 \times 2.5 \times 10^{-6}} = 2.5 \times 10^{6}$$

points, each of which must be 1/12 of the cloud height. For clouds 2400 ft. high, this requires 2,500,000 200-ft. towers spaced 800 ft. apart. Conceding these calculations to be largely in error, there is, nevertheless, little indication that lightning may be prevented by conduction currents from points. For cases of more rapid charge accumulation, the number of towers required would be correspondingly greater.

## TANKS

The use of tanks for oils which are dangerously inflammable has been discussed in relation to induced discharges. These same tanks made entirely of metal can be made to furnish, unaided except by good grounds, protection to contents for direct hits. They need no further discussion.

## LIGHTNING RODS

Franklin when he gave instructions that conductors used for lightning rods should terminate at the upper extremity, with one or more points, and extend downward until they met permanently moist earth possessed of good powers of electric conduction showed knowledge of the fundamentals of lightning rod protection far beyond that of his associates. These fundamentals are, however, insufficient for the whole solution of the problem, and must be supplemented by knowledge of lightning phenomena developed since the time of Franklin, such as was reported by Sir Oliver Lodge[8] and added to by the engineers and physicists of today.

In fact, with all our knowledge of these phenomena, such as side flashes, back strokes, electrical inertia, and the effect of location, ground conditions, etc., there

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5, 6, 7. Loc. cit.

8. Loc. cit.

seem to be no general rules which can be applied to all places to be protected, and these rules are sufficiently comprehensive to make unnecessary a special study of practically each location for which protection is desired.

For oil in storage, it seems best to have the rods take the form of high towers, placed as far from the reservoirs and as far apart as practical, being at the same time near enough to each other to make almost impossible any hits to objects between them. Each tower so erected should be grounded at its base to the water plane below the tower, to all piping around the base of the tower, and to the reservoirs for which protection is being provided.

FIG. 8—SPREAD OF DISCHARGE CURRENT OVER A CONCRETE FLOOR

To avoid so far as practical, any danger from side flashes which might ignite the oil, the towers are erected at some distance from the reservoir they are to protect. Good grounds directly under the towers also assist in reducing the possibility of side flash. Fig. 8 shows a current of electricity that appears to spatter all over the surface of a concrete floor with no special provision for good grounding when a condenser is discharged into the floor. There is no evidence of this flow of current over the floor surface when it is well grounded.

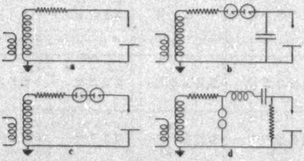

FIG. 9—DIAGRAMS OF CONNECTIONS FOR FURNISHING DISCHARGES

a A-c. 50 cycles
b D-c. with condenser
c D-c. pulsating
d Surge generator

Having decided to consider high towers well grounded, the next step was the making of many experiments to determine the protection area about rods as single units and in groups, as set up on models in the high voltage laboratory. In making these experiments, many tests were made with a-c., 50-cycle sparks, d-c. sparks with and without condensers both for grounded positive and grounded negative terminals, and for discharges from a surge or lightning generator.[9] Connections used are shown in Figs. 9A, B, C, and D.

Results of the tests made for all types of discharge used show no absolute immunity for any area around a rod. The tests were made on models having the storm centers two and four rod heights off center. Considered from a statistical viewpoint, the number of hits within a circle having one rod height as a radius and with its center at the rod was practically nil, but there was an occasional hit even within this area which was not taken by the rod.

As the area under consideration is increased by considering larger boundary circles drawn about the rod, the number of hits which can strike within a given area is increased until, at a distance of four times rod height from the rod, a circle may be drawn as indicative of the fact that beyond this point the rod furnishes little or no protection.

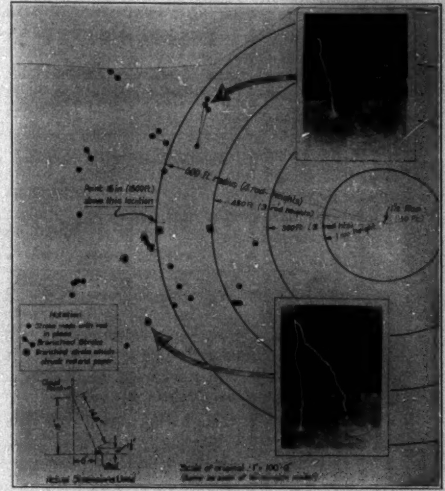
600 ft. radius (4 rod heights)
450 ft (3 rod heights)
300 ft (2 rod hts)
1 rod height
Point 15 in (1500 ft.) above this location
Notation
Strokes made with rod in place
Branched Stroke
Branched stroke which struck rod and paper
Scale of original 1" = 100'-0"

FIG. 10—DISTRIBUTION OF HITS FROM DISCHARGE NEEDLE OVER POINT FOUR ROD HEIGHTS AWAY FROM ROD AND TEN ROD HEIGHTS ABOVE SURFACE

Results of some typical tests are shown in Fig. 10 and Tables I, II, and III. These tests show the statistical protection values for single rods for areas enclosed by circles having radii of one, two, three, and four rod heights. All tests of this type were made with apparatus set up to scale, the rod in each case being considered as 150 ft. high. The actual rods used varied in height from ¼ in. to two in., with actual sparking distances varying from about two in. to almost 27 in.

Having determined in the laboratory what one rod

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[9] Loc. cit.

TABLE I. PROTECTION AFFORDED BY SINGLE RODS FOR AREAS SURROUNDING THE RODS

These results are from tests made with surge-generator discharges from a point representing a cloud center located at various distances above the plane and at a horizontal distance of 4 *h* from the center line of the rod whose height is *h*, equivalent to 150 ft.

The areas in which strokes were recorded are circles of which the rod is the center and whose radii were respectively *h*, 2 *h*, 3 *h*, and 4 *h*.

| Scale | Rod height | Point (cloud) height | | No. of strokes with rod and without rod | Circle with radius = 4 *h* | | | Circle with radius = 3 *h* | | | Circle with radius = 2 *h* | | | Circle with radius = 1 *h* | | | Strokes to rod |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Strokes to plane within circle | | Per cent. protection | Strokes to plane within circle | | Per cent protection | Strokes to plane within circle | | Per cent protection | Strokes to plane within circle | | Per cent protection | |
| | | Actual in. | To scale, ft. | | With rod | Without rod | | With rod | Without rod | | With rod | Without rod | | With rod | Without rod | | |
| 1 in. = 600 ft. | ¼ in. = 150 ft. | $1^2/_3$ | 1000 | 50 | 6 | 35 | 83 | 2 | 2 | 0 | 0 | 0 | ? | 0 | 0 | ? | 21 |
| | | 2½ | 1500 | 50 | 10 | 25 | 60 | 1 | 11 | 91 | 0 | 3 | 100 | 0 | 1 | 100 | 20 |
| | | $3^1/_3$ | 2000 | 50 | 7 | 16 | 56 | 4 | 8 | 50 | 1 | 3 | 67 | 0 | 0 | ? | 30 |
| | | 5 | 3000 | 50 | 7 | 19 | 63 | 2 | 11 | 82 | 0 | 2 | 100 | 0 | 0 | ? | 15 |
| | | $6^2/_3$ | 4000 | 50 | 2 | 16 | 87 | 1 | 10 | 90 | 0 | 7 | 100 | 0 | 3 | 100 | 0 |
| | | 8 | 4800 | 50 | 1 | 18 | 95 | 0 | 15 | 100 | 0 | 3 | 100 | 0 | 0 | ? | 21 |
| | | 10 | 6000 | 50 | 0 | 14 | 100 | 0 | 9 | 100 | 0 | 2 | 100 | 0 | 0 | ? | 23 |
| 1 in. = 400 ft. | $^3/_8$ in. = 150ft. | 2½ | 1000 | 50 | 12 | 24 | 50 | 1 | 9 | 11 | 0 | 0 | ? | 0 | 0 | ? | 15 |
| | | $3^1/_3$ | 1333 | 50 | 8 | 20 | 60 | 2 | 6 | 67 | 0 | 1 | 100 | 0 | 0 | ? | 22 |
| | | 5 | 2000 | 50 | 14 | 20 | 30 | 3 | 11 | 73 | 0 | 5 | 100 | 0 | 1 | 100 | 20 |
| | | $6^2/_3$ | 2667 | 50 | 8 | 23 | 65 | 2 | 14 | 86 | 1 | 6 | 83 | 0 | 1 | 100 | 9 |
| | | 8 | 3200 | 50 | 1 | 19 | 95 | 1 | 12 | 92 | 0 | 7 | 100 | 0 | 1 | 100 | 33 |
| | | 10 | 4000 | 50 | 2 | 19 | 89 | 0 | 14 | 100 | 0 | 6 | 100 | 0 | 2 | 100 | 26 |
| 1 in. = 300 ft. | ½ in. = 150 ft. | $3^1/_3$ | 1000 | 50 | 17 | 33 | 48 | 5 | 5 | 0 | 0 | 1 | 100 | 0 | 1 | 100 | 9 |
| | | 5 | 1500 | 50 | 13 | 32 | 59 | 1 | 14 | 93 | 1 | 5 | 80 | 0 | 1 | 100 | 11 |
| | | $6^2/_3$ | 2000 | 50 | 11 | 19 | 42 | 4 | 9 | 56 | 0 | 6 | 100 | 0 | 1 | 100 | 11 |
| | | 8 | 2400 | 50 | 4 | 33 | 88 | 1 | 19 | 95 | 0 | 6 | 100 | 0 | 2 | 100 | 33 |
| | | 10 | 3000 | 50 | 2 | 12 | 83 | 1 | 4 | 75 | 0 | 2 | 100 | 0 | 0 | ? | 26 |
| 1 in. = 200 ft. | ¾ in. = 150 ft. | 5 | 1000 | 50 | 26 | 27 | 4 | 4 | 10 | 60 | 0 | 0 | ? | 0 | 0 | ? | 3 |
| | | 7½ | 1500 | 50 | 24 | 25 | 4 | 6 | 14 | 57 | 0 | 2 | 100 | 0 | 0 | ? | 6 |
| | | 10 | 2000 | 50 | 10 | 21 | 52 | 1 | 5 | 80 | 0 | 0 | ? | 0 | 0 | ? | 26 |
| | | 12½ | 2500 | 50 | 7 | 18 | 61 | 1 | 14 | 93 | 0 | 3 | 100 | 0 | 0 | ? | 14 |
| | | 15 | 3000 | 50 | 7 | 21 | 67 | 0 | 14 | 100 | 0 | 8 | 100 | 0 | 2 | 100 | 19 |
| 1 in. = 150 ft. | 1 in. = 150 ft. | $6^2/_3$ | 1000 | 50 | 29 | 18 | 0 | 7 | 4 | 0 | 0 | 0 | ? | 0 | 0 | ? | 0 |
| | | 10 | 1500 | 50 | 21 | 22 | 5 | 8 | 13 | 39 | 0 | 3 | 100 | 0 | 0 | ? | 15 |
| | | $13^1/_3$ | 2000 | 50 | 10 | 19 | 47 | 1 | 9 | 89 | 0 | 3 | 100 | 0 | 0 | ? | 21 |
| | | $16^2/_3$ | 2500 | 50 | 6 | 26 | 77 | 1 | 17 | 94 | 0 | 7 | 100 | 0 | 1 | 100 | 22 |
| | | 20 | 3000 | 50 | 1 | 16 | 94 | 0 | 10 | 100 | 0 | 5 | 100 | 0 | 2 | 100 | 30 |
| 1 in. = 100 ft. | 1½ in. = 150 ft. | 10 | 1000 | 50 | 21 | 32 | 34 | 5 | 5 | 0 | 1 | 0 | 0 | 0 | 0 | ? | 8 |
| | | 15 | 1500 | 50 | 14 | 29 | 52 | 4 | 14 | 71 | 0 | 1 | 100 | 0 | 0 | ? | 15 |
| | | 20 | 2000 | 50 | 4 | 14 | 71 | 1 | 4 | 75 | 0 | 0 | ? | 0 | 0 | ? | 8 |
| | | 25 | 2500 | 50 | 5 | 26 | 81 | 2 | 11 | 82 | 0 | 0 | ? | 0 | 0 | ? | 32 |
| 1 in. = 75 ft. | 2 in. = 150 ft. | $13^1/_3$ | 1000 | 50 | 22 | 29 | 24 | 7 | 6 | 0 | 0 | 0 | ? | 0 | 0 | ? | 6 |
| | | 20 | 1500 | 50 | 14 | 23 | 39 | 3 | 9 | 67 | 1 | 1 | 0 | 0 | 0 | ? | 14 |
| | | $26^2/_3$ | 2000 | 50 | 7 | 21 | 67 | 0 | 12 | 100 | 0 | 3 | 100 | 0 | 0 | ? | 35 |

TABLE II

PROTECTION AFFORDED BY SINGLE ROD

Summary of laboratory tests with various sources of potential when storm center is four times the rod height from a vertical line through the rod. On the scale used, the rod height is 150 ft. and the average cloud height is 2578 ft. With each source of potential 900 strokes were made with the rod and 900 without the rod. One rod height = *h*.

| | | D. C. (Pulsating) | A. C. 50 Cyc. | D. C. with Condenser | Surge Generator |
|---|---|---|---|---|---|
| Circle with Radius = 4 *h* | Hits with rod | 227 | 256 | 261 | 125 |
| | Hits without rod | 401 | 386 | 415 | 397 |
| | Per cent protection | 43 | 34 | 37 | 69 |
| Circle with Radius = 3 *h* | Hits with rod | 74 | 76 | 67 | 31 |
| | Hits without rod | 198 | 168 | 148 | 183 |
| | Per cent protection | 63 | 55 | 55 | 83 |
| Circle with Radius = 2 *h* | Hits with rod | 15 | 7 | 2 | 3 |
| | Hits without rod | 77 | 63 | 47 | 65 |
| | Per cent protection | 83 | 89 | 96 | 96 |
| Circle with Radius = *h* | Hits with rod | 0 | 0 | 0 | 0 |
| | Hits without rod | 19 | 19 | 12 | 14 |
| | Per cent protection | 100 | 100 | 100 | 100 |
| No. of strokes to rod | | 278 | 181 | 333 | 345 |
| Per cent of 900 strokes to rod | | 31 | 20 | 36 | 38 |

TABLE III

PROTECTION OF A SINGLE ROD

Summary of laboratory tests when the storm center is twice the rod height from a vertical line through the rod. On the scale used, the rod height is 150 ft. and the average cloud height is 2578 ft. With each source of discharge used 900 strokes were made with the rod and 900 strokes without the rod. One rod height = h.

| | | D. C. (Pulsating) | A. C. 50 Cyc. | D. C. with Condenser | Surge Generator |
|---|---|---|---|---|---|
| Circle with Radius = 4*h* | Hits with rod | 208 | 192 | 147 | 61 |
| | Hits without rod | 721 | 662 | 774 | 650 |
| | Per cent protection | 71 | 71 | 81 | 92 |
| Circle with Radius = 3*h* | Hits with rod | 129 | 108 | 134 | 16 |
| | Hits without rod | 562 | 501 | 614 | 495 |
| | Per cent protection | 77 | 76 | 78 | 97 |
| Circle with Radius = 2 *h* | Hits with rod | 39 | 26 | 45 | 3 |
| | Hits without rod | 318 | 263 | 332 | 264 |
| | Per cent protection | 88 | 90 | 86 | 99 |
| Circle with Radius = *h* | Hits with rod | 1 | 0 | 0 | 0 |
| | Hits without rod | 94 | 66 | 81 | 74 |
| | Per cent protection | 99 | 100 | 100 | 100 |
| No. of strokes to rod | | 584 | 615 | 710 | 675 |
| Per cent of 900 strokes to rod | | 65 | 68 | 79 | 75 |

will do, combinations of rods using 2, 3, 4, and 6 rods set on the circumference of circles were tried. Many tests were made with the rods grounded and connected to one side of the circuit, and an electrode above the center of the circle, on the circumference of which the rods were located. The rods took a large share of the hits, but it was entirely possible to make a portion of them strike the area within the circle when that circle had a radius of 4 rod heights. For smaller circles the number of hits inside was less. Also the protection factor increased with increase in sparking distance, or height of point above the plane of the rods.

Data about cloud height showed thunder clouds for Southern California to have a height of 2000 to 6000 ft. above the earth.[10] The preliminary work while far from complete suggested as a probable safe spacing of protective towers such that no portion of the area to be protected would be more than 2½ times a tower height from a tower.

To check this hypothesis, a model of one of the important storage farms to be protected was made to the scale of one inch equals 100 ft.

In making the protection plan, the model was tested first with towers only, the towers being adjusted as to location and height until it was practically impossible to make any discharges hit the miniature reservoirs. It was considered unnecessary to make it impossible to get a discharge to structures representing steel tanks. After the reservoirs were thus fully protected, some connecting cables were added at the 150 ft. level and another group of tests was made to test their effect. As a further precaution, each cable has, at the middle point of the spare between towers, a vertical cable extending downward from the aerial cable to the ground cable.

Each tower at its base, is grounded by means of a well drilled to permanent water and is also tied in to the water pipe system which is installed in such a way as to form a complete loop around each reservoir. The reinforcing steel of each reservoir is also connected to this grounding system.

In conclusion, it may be said that the authors feel that very good protection has been provided for the oil reservoir farms of California. It is urged, however, that more knowledge of lightning phenomena be gained as rapidly as possible. As a step in this direction many towers which have been erected are being equipped with fusible tips and klydonograph attachments to make it possible to get records of hits to towers.

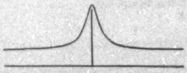

FIG. 11—EQUIPOTENTIAL LINE AROUND A CONDUCTING ROD UNDER A CLOUD

This plot was obtained by the formula quoted by H. V. Ingersoll in his thesis. The potential of any point $(x, y)$ on the line is 5. The potential of the cloud is 100 and the potentential of the earth is 0. The height of the cloud above ground is 6.69 and the height of the rod is 1.22. In the plot the vertical scale is 2½ times the horizontal scale.

## Appendix

Inasmuch as grounded conducting towers do act as lightning rods, it would be natural to expect that some law of influence of a rod in space upon the electric field about that rod may be found. A search of literature for results of such studies and a series of tests to determine the effect of conducting rods upon an adjacent electric field were planned. The tests have not been completed and results which can be considered conclusive have not been obtained as yet, but a large number of tests and two equations found in a thesis of H. V. Ingersoll, indicate something worthy of attention.

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[10] Loc. cit.

The equations are

$$\Phi = \frac{\dfrac{\Phi_2 - \Phi_1}{l\sqrt{2}}}{\sqrt{(y^2 - x^2 - d^2) + \sqrt{(y^2 - x^2 - d^2)^2 + 4\,x^2\,y^2}}} + \Phi_1$$

and

$$v = \frac{\dfrac{}{h\sqrt{2}}}{\sqrt{(y^2 - x^2 - h^2) + \sqrt{[-(y^2 - x^2 - d^2)]^2 + 4\,x^2\,y^2}}}$$

The first of these equations was developed at the California Institute of Technology, whereas the second one is taken from a paper by Dr. Charles H. Lees published in the proceedings of the Royal Society of London, 1915.

In the first equation the following symbols are used:

$\Phi$ = potential at a point $(x, y)$
$\Phi_2$ = potential at a cloud
$\Phi_1$ = potential at ground
$l$ = height of cloud above ground
$d$ = height of rod.

In the second equation the symbols used are:

$v$ = potential at a point $(x, y)$
$h$ = height of rod
$\frac{\alpha\,\pi}{h}$ = vertical potential gradient at point $(x, y)$.

If the vertical potential gradient is constant over the whole area then $\frac{\alpha\,\pi}{h}\;\frac{v_2 - v_1}{l}$

where

$v_2$ = potential of cloud
$v_1$ = potential of ground
$l$ = distance between cloud and ground.

The equation now is

$$v = \frac{\dfrac{v_2 - v_1}{\pi\,l\sqrt{2}}}{\sqrt{(y^2 - x^2 - h^2) + \sqrt{[-(y^2 - x^2 - h^2)]^2 + 4\,x^2\,y^2}}}$$

With $\Phi_1$ and $v_1$ taken as zero and Dr. Lees' equation multiplied by $\pi$ to get both equations in the same system of units the equations are identical.

Fig. 11 shows a curve plotted by use of these equations.

Figs. 12, 13, and 14 show charts obtained by means of a salt tray with one, two, and three rods respectively.

The salt tray used was 21 in. by 25 in. in size.

The bottom was a true plane kept level and then covered to a depth of ¼ in. with tap water.

Fig. 15 shows the arrangement used in making the tests.

An attempt was made to get from men with several years of experience at industrial plants, such as smelters with high stacks, located in places subject to considerable lightning reports of hits with relation to tall stacks equipped with lightning rods.

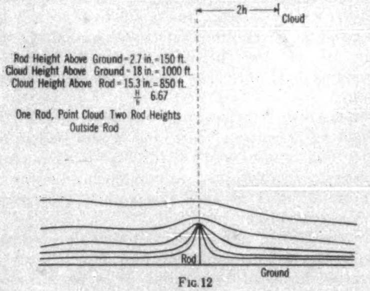

FIG. 12

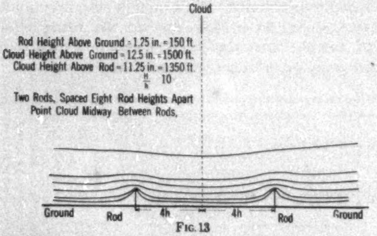

FIG. 13

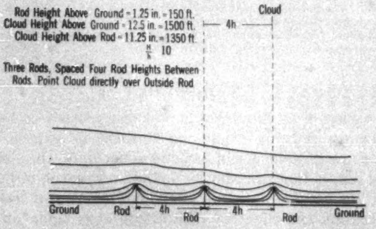

FIG. 14

FIGS. 12, 13, AND 14—EQUIPOTENTIAL LINES BETWEEN CLOUDS AND GROUND WITH DIFFERENT ARRANGEMENTS OF RODS

Charts plotted from tests made with salt tray shown in Fig. 15

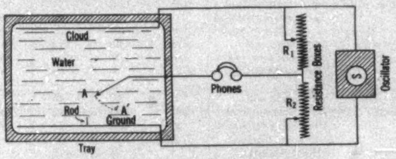

FIG. 15—DIAGRAM OF TESTS TO DETERMINE EQUIPOTENTIAL LINES WITH VARIOUS ROD ARRANGEMENTS

The reports are somewhat in disagreement and do not furnish material from which positive conclusions may be drawn, but there are a number of cases of reports backed by competent and careful observations which state that lightning often hits close to high stacks properly equipped with good lightning rods, without striking the rod.

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## Discussion

For discussion of this paper see page 181.

# Lightning Protection for the Oil Industry

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Associate, A. I. E. E.

***Synopsis.**—Building safe storage for the products of the oil industry is quite a different problem from making the storage already in use safe from fires started by lightning. The latter problem is discussed with some principles to be observed. Details of construction are so varied that it is difficult to give general rules. A record of several hundred installations over a period of about three years is given.*

*Work with small models in the laboratory has been successful in some cases. It is unwise to rely too much on work of this kind, however.*

*Since the seat of the charge under a storm cloud is largely on pipe lines, tanks, and other metal parts in the oil fields, lightning devices should be securely attached to these structures. A network of pipe lines at or near the surface makes a better ground for towers than a single shaft driven vertically downward to permanent moisture.*

* * * * *

## LIGHTNING PROTECTION FOR OIL STORAGE

ANY problem connected with lightning is difficult on account of the magnitude of the quantities involved. Because of the inflammability of hydrocarbons, the complexity of the operations, the great haste, and vast extent of the oil industry, any problem bearing on fire prevention in the petroleum field presents great difficulty. When we associate the two in an attempt to design protection against lightning for the oil industry, the problem is very complex and its solution will not be simple nor easily attained. Any hope of success in such an undertaking must rest on first-hand knowledge of the conditions under which fires most frequently occur, knowledge of details of construction, the varieties of construction used by different companies, special hazards arising from daily operations, and the effects of corrosion.

There are two distinct phases to consider; first, to design an oil tank which will be inherently safe against lightning; and second, to design a system which will offer a high degree of protection for the storage tanks *in actual use* today throughout the oil industry.

The solution of the first is easy and is probably exact. Theory and practise both indicate that the modern all-steel, gas-tight tank is the best type of construction. The solution of the second problem is difficult and at best will result in an approximation, but for the present it is the more important. There are millions of dollars invested in unsafe storage tanks and the aim is to give this property the highest possible degree of protection and at a reasonable cost. It is the purpose of this paper to discuss the design and construction of protective devices for oil storage tanks now in use.

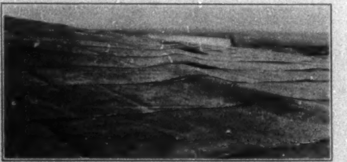

FIG. 1—SHOWING THE EFFECTS ON METAL SHEETS NAILED TO WOOD DECKS CAUSED BY TEMPERATURE CHANGES AND BY FILLING AND EMPTYING THE TANK. IN MANY CASES THE EFFECTS OF CORROSION ARE JUST AS BAD

Oil is stored in various containers. The most common are steel tanks, spaced on 300-ft. centers, usually about 115 ft. in diameter, 30 ft. high, and having a capacity of 55,000 barrels. Although the tendency is definitely toward the use of steel decks for such tanks, a large number still have wooden roofs or decks, covered with sheets of galvanized iron or vapor-resisting paper and waterproofed fabric. In some localities, corrosion is so bad that steel decks last less than two years and only a wooden deck can be used. This is particularly true where the sulphur content of the crude oil is high. In California and also in the mid-continent field there are a number of earthern reservoirs most of which are lined with reinforced concrete and covered with wood decks similar to those used on tanks. Some of these are circular, having a radius of 250 ft. or more, while others are ovals of radius 300 or 400 ft. and length 600 to 1500 ft. The capacities run from 500,000 to 5,000,000 barrels.

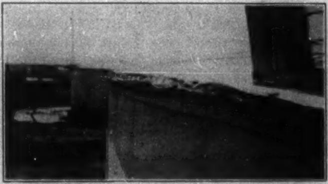

FIG. 2—A MINOR DISCHARGE BETWEEN THE ROOFING MATERIAL AND THE VERTICAL STEEL SHELL AT THE EAVES OF A TANK WHICH IS NOT VAPOR-TIGHT MAY BE THE CAUSE OF A FIRE

It is common practise throughout the oil fields to gage and sample the oil from hatches on the deck. There are generally from one to four such gaging hatches per tank and there are several designs with various methods of closing but few of which can be considered gas tight.

If this brief description properly defined the problem,

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[1] Of the Johns-Manville, Inc., New York, N. Y.

*Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., Sept. 13-16, 1927.*

much could be done in an experimental way with models. Unfortunately, however, there is a great mass of detail which seriously complicates the problem. Other tank fittings and arrangements of pipes vary so widely from one company to another that it is necessary to examine the design and installation of each company, and frequently of each tank, for appliances which are liable to give rise to sparks during electrical storms. Special hazards introduced by the location and character of structures near oil storage complicate the problem still further and discount any scheme of protection which is based entirely on the behavior of models of isolated miniature tanks and devices in the laboratory.

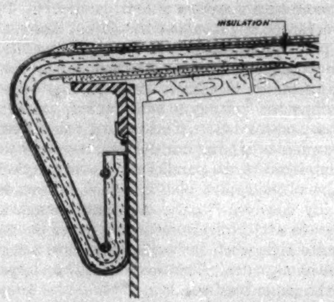

Fig. 3—Cross-Section of the Eaves Construction which is Flexible and Vapor Tight. It is Composed of Heat Insulation, Usually Hair Felt, and Roofing Fabrics

While the main lightning discharge is so powerful that it is liable to cause fires under any conditions, it is not necessary that an oil container receive a direct lightning discharge in order to cause a fire. Some years ago when little or no precaution was taken in the refineries against escaping gases, it was not uncommon to have a number of fires resulting from a single lightning flash in the vicinity of the refinery. Under such conditions, only a small spark is necessary to cause a fire, and it is well known that such sparks due to the surge of electric quantity across the earth's surface or to induction have caused fires at a considerable distance from the point which received the main discharge from the cloud. To illustrate, one large company erected a tower about 120 ft. high in one of its tank farms. A few weeks later the tower was struck and two tanks were fired, one tank about 200 ft. away and the other tank about 900 ft. from the tower. The disastrous fire at Monterey, California in 1924 was caused by lightning setting fire to a tank when the main discharge was received by a tree 780 ft. away. The reservoir fire at Coalinga in 1924 was caused by lightning although the actual flash was seen to strike on or near a pipe line about a quarter of a mile from the reservoir. The great reservoir fires at San Luis Obispo and at Brea, California in April 1926 were unquestionably caused by lightning. It is not known whether the latter fires were caused by direct hits or by minor sparks which accompanied the lightning discharge. The reservoir fire at Bakersfield a few weeks later was reported to have been caused by a direct strike of lightning which tore a hole in the deck. This reservoir was a simple earthern pit without reinforced concrete lining and it contained fuel oil.

It is impossible to say what percentage of oil fires have been caused by direct hits and what percentage by small sparks or secondary effects, but from the available data, it is reasonable to conclude that a large majority was caused by secondary lightning discharges.

Evidently, in the daily handling of large quantities of inflammable material and in the storage of such material in containers that are not actually gas tight, there is great danger that small sparks, which always accompany lightning discharges, may cause a fire even though the main discharge be several thousand feet away. Sparks caused by the surge over surfaces of varying resistance or along several paths of different impedance, when the earth's charge disappears at the instant of a lightning flash, are most certainly the cause of a majority of the fires and explosions in the oil fields.

In a general way, there are three conditions to fulfill for the prevention of fires on oil property set by minor discharges:

1. With the exception of one breathing vent, the containers must be kept closed,
2. Isolated pieces of metal in or near the vapor space must be grounded and all loose joints between metal parts must be eliminated to prevent the possibility of sparks,
3. The vulnerable areas should be enclosed by a Faraday cage or network, completely enclosing the non-metallic parts and securely grounded.

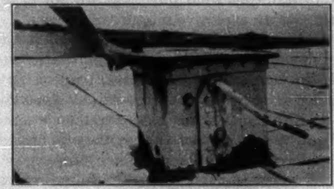

Fig. 4—A Winch Box on the Deck. The Cover is not Vapor Tight

When it is realized that all this must be done at small cost, without cleaning the tanks, and frequently when the tanks are filled with oil, the magnitude of the problem is apparent.

The design and construction of a suitable network or cage is the most important thing to be discussed here. Such a network was first designed and applied to wooden roofed tanks which had been covered with heat insulation and had been made vapor tight with flexible materials to prevent evaporation losses.

If a network of wires is placed under the heat insulation and roofing material, the wires would have to be very close together to prevent sparks between and below the plane of the wires, in or near the metallic fittings on the deck. There is danger also that when under storm conditions the charge on the deck is suddenly released by a lightning discharge, the roofing material may be punctured. This is particularly likely to happen at the edges of tank fittings or at the eaves where shallow pools of water may collect directly over the angle irons of the tank. If some material such as poultry netting is used there is great danger of sparks at the mechanical junctions where the netting is attached to the tank and at the edges of the strips of netting since all junctions must be purely mechanical. If a network of small mesh wire is placed directly over the roof and resting on it, there is the same danger of sparks occurring and, in addition, it would be again particularly difficult to deal with tank fittings where gases escape during changes of temperature of the vapor space or during the time the tank is being filled. Since only mechanical junctions are permissible, and these are very likely to spark during high-potential discharges, it is important that such junctions are not in a region where there is an explosive mixture of gases.

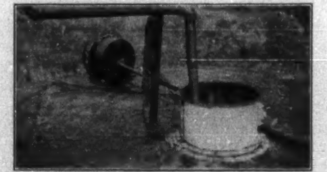

FIG. 5—AN OVER-SHOT FILLING PIPE PASSING THROUGH A LARGE HATCH ON THE DECK

This factor, as well as the high cost of installing a network of small mesh and the danger that it would be damaged by workmen on the tank, made it necessary to consider a network of wires raised some distance above the deck. If wires were stretched across the deck it is necessary first of all that they be high enough so men can work under them. Since the purpose of the system of wires is to reduce the charge which may collect on the deck under storm conditions, and to provide a low-resistance path to ground when a lightning discharge occurs, the network must be grounded in a satisfactory manner. It should be securely attached to the tank itself and additional precaution should be taken to protect the eaves of the tank, since it is well known that most of the fires start there. The most obvious design then was a system of wires extending radially from a central wooden post at the peak of the deck to a cable supported above the eaves. This cable would have to be about 7 ft. above the eaves and supported preferably by metallic members attached to the tank as securely as possible without welding. It was necessary then to determine how far apart such wires should be and, if possible, to measure the degree of protection that such a distribution of conductors would offer, or at least find the ratio of the charge on the elevated conductors to the charge on the tank roof when a charged cloud was overhead.

Preliminary tests were made on a wooden platform about 12 by 20 ft. covered with hair felt and saturated paper similar to the construction for vapor tight tank roofs. This deck was set up 2 ft. above the floor in a large room with a system of four parallel No. 4 copper wires arranged 6½ ft. above the deck. The spacing of these parallel conductors was varied during the course of the experiments from a few feet up to the entire length of the deck. Above these parallel wires was a cloud of poultry netting, 10 by 24 ft., suspended from the ceiling by cotton tape. This netting was connected to one terminal of a large transformer; the other terminal was connected to the parallel wires over the deck. At one edge of the roofing platform, this grid was dropped vertically downward to the deck and grounded. The surface resistivity of the saturated paper on the deck was quite high when the surface was dry, being about 100,000 ohms per cm. This was reduced by a large factor when the paper was wet.

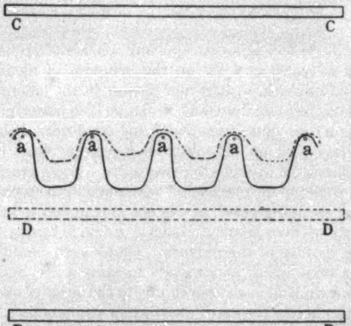

FIG. 6—EQUIPOTENTIAL LINES IN THE CURRENT SHEET. THE FRACTION OF THE CURRENT WHICH FLOWED TO THE GRID (*a a a*) INDICATES THE AMOUNT OF SCREENING PRODUCED BY THE GRID IN THE ELECTROSTATIC CASE

A number of methods was tried for determining the potentials at points in the field between the deck and the poultry netting, particular attention being given to the region between the deck and the plane of the grid. None of the methods tried was considered satisfactory. However, equipotential surfaces were plotted and it was estimated, from the shape of these equipotential surfaces, that the amount of protection given was about 75 per cent.

The equipotential lines in a current sheet can be easily studied and this gives a simple method for getting the required information. Accordingly, apparatus was set up to represent the cloud, a parallel grid and the earth in cross-section and the work carried out in a small horizontal glass tray. Referring to Fig. 6 *C C* is the cloud, *D D* the deck or plane to be protected and *a a a* is the grid; that is, the points of intersection of the wires with the vertical plane perpendicular to the wires. The tray had a plate glass bottom about 24 by 36 cm. and contained dilute salt solution to a depth of about 0.3 cm. The cloud (*C C*) was a bar of brass and formed one terminal for the current sheet in the tray. The protecting wires (*a a a*) were small pointed brass rods screwed into a horizontal bar supported above the water. These rods were all adjusted in length so that they just touched the glass tray. The bar holding these rods was connected to the bar (*D D*) representing the deck and these together formed the other terminal. Using low voltage, 500 cycles, equipotential lines as shown in Fig. 6 were obtained by using a telephone receiver and exploring points.

When *D D* was moved downward to the new position *D′ D′* the equipotential surface dropped down as indicated in the figure. In order to get some idea of the screening action of the grid, the bar holding the points (*a a a*) was disconnected from *D D* and the currents which flowed from *C C* to the grid and to the deck (*D D*) were measured. These currents were measured for a number of different positions of the cloud *C C* and of the deck. Also the spacings of the points *a a a* were changed. The ratio of the current flowing to *a a a* and to *D D* was taken to be the value of the protection offered to the plane *D D* by the wires (*a a a*). This ratio was practically independent of the position of *C C* so long as *C C* was more than three times the spacing of *a a a*. It depended very much, however, upon the spacing between the wires (*a a a*) and the distance from these wires to the plane (*D D*). So long as the bar (*C C*) was some distance away from the grid the ratio of the spacing of the grid to the elevation above *D D* determined the amount of protection.

Maxwell calculated the screening effect of a grating of equally spaced parallel wires on a plane surface parallel to the grating. This is the simplest case and is probably the only one that has been solved mathematically. The formula derived by Maxwell[2] gives the density of charge induced on the lower plane when the grating is interposed. The density of this charge is to that induced if the grating were removed as

$$1 : 1 + \frac{b_1 b_2}{\alpha (b_1 + b_2)} .$$

where $b_1$ is the distance from the grating to the lower plane, $b_2$ the distance from the grating to the upper plane and $\alpha$ is a function of the spacing of the wires given by the following expression:

$$\alpha = - \frac{a}{2 \pi} \log \left( 2 \sin \frac{\pi c}{a} \right)$$

| Spacing of wires | Height of wires | Calculated protection |
|---|---|---|
| 3 ft. | 7 ft. | 86 per cent |
| 5 ft. | 7 ft. | 75 per cent |
| 7 ft. | 7 ft. | 66 per cent |
| 3 ft. | 10 ft. | 90 per cent |
| 5 ft. | 10 ft. | 81 per cent |
| 7 ft. | 10 ft. | 73 per cent |
| 10 ft. | 10 ft. | 65 per cent |

A large number of readings were made then with the current sheet to get values indicated for the protection offered by a grid. The percentages were all from 1 to 6 per cent higher than those calculated. While the experimental method is probably not capable of great accuracy, it did indicate a procedure for studying cases which are too complicated for mathematical solution.

The experiment with the current sheet is so simple and the results obtained were apparently so satisfactory that it was decided to study the cross-sections of details on a much larger scale. A large piece of plate glass 40 by 60 in. was used as a tray. A cross-section of a storage tank was inserted at the base of the tray over which was arranged a cross-section of the proposed network. The currents flowing to the cross-section of the deck and to the grid were again measured. In this case, the deck was receiving 13 per cent of the total current.

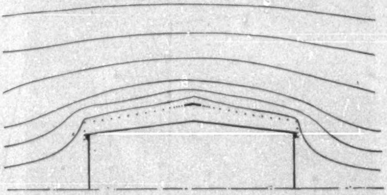

Fig. 7—Cross-Section of a Tank Protected by a System of Parallel Wires 7 Ft. or More Above the Deck. The Actual Model in Use was 2 Per Cent of the Diameter of a 55,000 Barrel Tank

The records of tank fires show that in a large majority of cases, the fires start at the eaves of the tank. Accordingly, a large model of the eaves construction was made and the proposed plan for the grid installed in cross-section. Fig. 8 shows the reproduction of the equipotential lines traced for the eaves construction. It was not found possible with this arrangement to trace equipotential lines under the grid when the wires are placed very close together on the vertical bracket (*vv*). This model was made to scale, on the supposition that the cable at the top of the bracket was to be installed 7 ft. above the eaves and extend outward beyond the eaves, about 3 ft. It is evident that a network must not only cover the deck but it must enclose it. While a fairly large spacing of the wires is probably satisfactory over the deck, the region over and around the eaves should be protected with a wire net of small mesh.

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[2] "Electricity and Magnetism," Volume I, Article 203.

Since an actual installation gives a cage which is much more effective than a system of parallel wires, which this last model represented, it was necessary to build a model and devise a method for getting the effectiveness of a miniature network. So a tank model was made to be tested for the three-dimensional case. The tank was built of a wooden frame on the scale of 1 to 40 for the 55,000 barrel tank. Galvanized iron was used for the tank and a system of radial wires applied to scale according to the proposed scheme. The cloud consisted of one-in. mesh wire screening, 5 ft. by 10 ft. A vibration galvanometer was used merely as a sensitive a-c. ammeter to measure the charging current to the capacities formed by the network and the roof. Charging currents are proportional respectively to the capacities and to the charges that collect on the network and the roof. The results obtained this way were checked by using a ballistic galvanometer for comparing capacities. The ratio of the deflections gives directly the ratio of the charges desired. Measurements with the vibration galvanometer gave 96.8 per cent of the charge on the network. The ballistic galvanometer gave 98.4. This is the ratio of the charge which collects on the shell of the tank mode and the network to the charge which collects on the insulated metal tank top under the network.

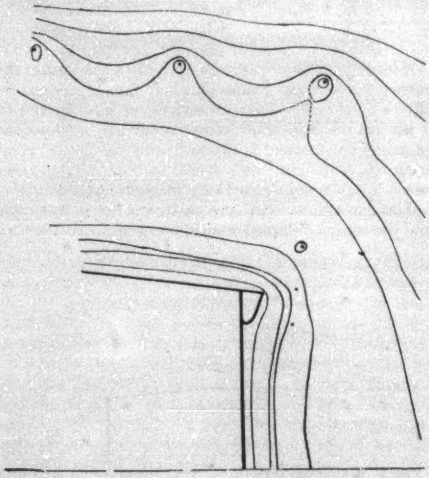

FIG. 8—EQUIPOTENTIAL LINES AT THE EAVES OF A TANK PROTECTED BY A SYSTEM OF WIRES. THE PROTECTION IS INCREASED BY PLACING WIRES CLOSE TOGETHER ON THE VERTICAL BRACKET *v v*

Some tests in the field have been made to get an approximate idea of the efficiency of this network as actually installed on a tank. The attempts to measure the effect directly indicate that the efficiency is greater than 90 per cent. A more accurate result cannot be given on account of the difficulty of measurement and the crudeness of the apparatus used. The method consisted in measuring simultaneously the quantities of electricity discharged, at the time of the lightning flash, from a section of the network itself and similar conductors protected by the network. An improvement of this method will in all probability yield valuable information concerning the size of mesh necessary to reduce secondary effects to an even greater safety.

The ratio of the spacing of the radial wires composing the network to the elevation above the deck has a maximum value of five to seven over surfaces which are poor electrical conductors. The minimum value of the spacing was 18 in. at the eaves. Certainly this spacing of wires is too great unless conditions are very favorable. It is of the greatest importance to eliminate poorly connected or isolated pieces of metal wherever possible. When this is not possible, it is necessary to use a screen of small mesh. The smaller the mesh the more complete the protection but the smaller the mesh the greater the cost and in most cases the greater the difficulty of application. Since most fires start at the eaves of the tanks it is advisable to increase the protection at this point. While the spacing of wires over the tank

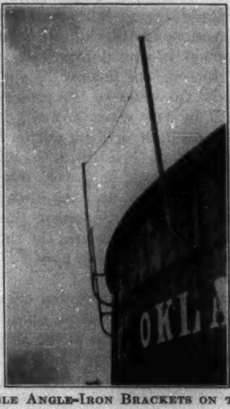

FIG. 9—DOUBLE ANGLE-IRON BRACKETS ON THE TOP RING OF THE TANKS HOLD THE PERIPHERAL CABLE TO WHICH THE RADIAL WIRES ARE ATTACHED

proper may be satisfactory the spacing in the vicinity of the eaves should not be greater than 1 ft. Welded mesh wire with a 4-in. spacing should be installed on the steel brackets. This mesh wire should be 6 ft. wide and should extend completely around the tank at the eaves. The lower edge of this mesh should be at least one ft. below level of the angle iron on top of the tank shell. Above this width of welded mesh, No. 12 wires should be installed one ft. apart on the brackets and on the radial wires over the eaves.

If economy were not an important consideration many special problems and difficulties could be avoided by using a network of sufficiently small mesh. A grid of wires may reduce effects to a very small fraction but this may not be enough if the structure to be protected is fundamentally bad, or when operating conditions are such that fires may be easily started. A large quantity of gas is given out when crude oil is pumped into a tank and a lightning discharge near the tank at this time is very dangerous regardless of the protective devices. When oil is pumped out of a tank the air entering makes an explosive mixture and a very small spark will destroy the tank.

The over-shot pipe which passes through an open hatch is still in daily use in some places and may occasionally be used in emergencies by the most careful oil men. A surge along this pipe line is likely to cause a spark where the pipe passes through the tank roof and of course such a spark would ignite any vapors present.

In most cases the breathing vent is installed on the deck. These vents, fitted with fine mesh screens, are usually low but in some cases extend 5 ft. or 6 ft. above the deck, and, in one case, over 20 ft. This extension was made so that if the vapors catch fire the flames will be high enough above the deck to prevent setting fire to the roofing materials. Probably the most satisfactory solution here is to avoid anything over 4 ft. high and to install a net of 2-in. mesh wire on top of the grid composing the main network.

A large number of special problems have been considered during the past three years. Much experimental work has been done with models of tanks, of reservoirs, of gas collecting systems, and other construction details, using various types of electrical discharges. In some cases the results of work seemed to be definite and conclusive but in the majority of cases such experiments were unsatisfactory. Several investigators have made use of small models and unquestionably much of value has been learned in this way. However, one thing brought out very clearly during the course of this study was that the greatest care must be exercised in the interpretation of results in laboratory tests on models. It is quite possible to make a device or small model and apparently prove it satisfactory when experience under actual conditions shows it is not. Even though the models, cloud elevations, and voltage are reduced to a convenient scale, there are some factors which cannot be so reduced and, what is just as important, there are always conditions in actual practise which are quite impossible to simulate. Unfortunately, it takes several years to accumulate information in the field which could be obtained in a few weeks in the laboratory. But if the field record is from a large number of applications and the time includes sufficient number of severe storms the information is, of course, of prime value.

The network essentially as previously described has been installed on about 800 tanks during the past three years. These tanks are well distributed from Pennsylvania and New York, through Louisiana, Texas, Oklahoma, Kansas to California. The first and the largest number of installations was made in the mid-continent fields where the damages from lightning in the past have been very heavy. In a group where there are over 100 protected tanks, one tank was fired by lightning just two years ago. There have been no losses in this group since. In an equal period of time, including nearly the same number of storms, prior to the installation of the networks, nine tanks in this group were fired by lightning.

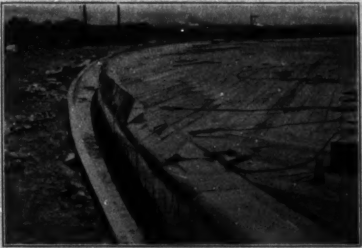

FIG. 10—WATER SEAL FOR THE EAVES OF A LARGE RESERVOIR IN COURSE OF CONSTRUCTION. THE TROUGH IS CONCRETE REINFORCED WITH WELDED MESH WIRE. SHEETS OF ZINC ARE NAILED TO THE DECK AND BENT DOWNWARD INTO THE TROUGH. THE WOOD DECK IS THEN COVERED WITH ROOFING PAPER

Several other fires have occurred on protected tanks, but always on tanks which, on account of operating conditions, were particularly susceptible, and which could not properly be considered to have a fair degree of protection. In two cases the hatches were open and the tanks were being filled with Oklahoma crude when the tanks received a direct lightning discharge. In two other cases the heat insulation and vapor tight roof had been installed over loose metal sheets. The oil had just been pumped out of these tanks leaving a mixture which exploded when struck by lightning, blowing the entire roof off the tanks. It is too much to expect a simple inexpensive network to protect tanks containing explosive mixtures and so constructed that there are numerous air-gaps between disconnected pieces of metal. Only one fire has occurred with conditions under which the network should have been effective.

In all other cases, the fires were due to changing conditions during the process of normal operation of moving the oil or due to causes otherwise avoidable. Eliminating those cases where for some reason the tanks were open, the reduction in the number of fires for a period of two and a half years amounts to over 90 per cent.

It is definitely known that some of these fires were started by primary discharges and it is probable that all were started in this way. Certainly some of the fires could have been prevented if towers had been used to protect the tanks from direct lightning discharges although in several cases recently reported, no fire was started when a direct lightning discharge was received by the network.

The large ground reservoirs presented new difficulties, but the enormous value concentrated into a relatively small space, justified greater expense in building a protective system. The cooperation of several of the California companies in working out details of construction, and their excellent scheme for reducing the oxygen content in the vapor space of the large reservoirs, by the introduction of flue gases, made possible a degree of protection of the highest order.

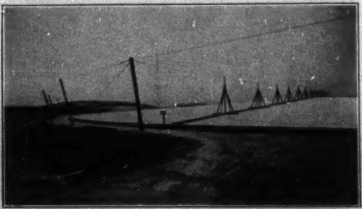

FIG. 11—CONSTRUCTION ON THE EMBANKMENT OF A LARGE RESERVOIR SHOWING THE PERIPHERAL CABLE, GRID AND, IN THE BACKGROUND, A STEEL TOWER

A million and a half barrels of oil may be stored under one roof, half underground, on about 10 acres which otherwise would require 30 tanks on at least 50 acres. These reservoirs usually have a lining of concrete reinforced with 6 by 6-in. welded mesh wire No. 6. The mesh is 10 ft. wide, lapped 6 in. on each strip and fastened together with short pieces of soft wire. This mesh wire is carried up to the eaves and is covered with concrete. The bottom of the reservoir usually contains several in. of water and above this the depths of oil may be as much as 30 ft. A number of pipe lines may lead into this reservoir, the main lines being usually 16- or 18-in. pipe. Surrounding the reservoir there is usually a three of four in. water line with fire hydrants, 300 or 400 ft. apart. Such pipe lines form the best means for grounding lightning devices.

The record of some appliances which have been in use for a number of years suggested that a peripheral cable grounded at frequent intervals is probably the most satisfactory and economical protection for the eaves of the ground reservoirs. If this is supplemented by a number of steel towers arranged around the reservoir, a high degree of protection should be obtained against primary lightning discharges. A grid of wires over, the entire deck would raise the charge under a storm cloud, above the deck and provide a path for the surge which otherwise would go over the deck when the cloud discharged.

Accordingly, telegraph poles were installed 40 ft. apart on the top of the embankment of the reservoirs about 12 ft. out from the eaves. These poles are 12 ft. above ground and are listed about 2 ft. outward from the reservoir. A $\frac{3}{8}$-in. stranded steel cable is supported near the top of these poles and extends completely around the reservoir. One or more guy wires, extending from each pole, are connected to this peripheral cable the guy wires serving the double purpose of mechanically strengthening the system and affording good grounding connection. These grounds consist of metallic screw anchors and are all connected together by an underground copper cable which, in turn, is grounded to all of the pipe lines in the vicinity of the reservoir.

A detail map of an area that has been developed by an oil company shows a maze of pipe lines of many sizes, steel tanks, ground reservoirs and, in many cases, stills and steel towers if the storage is near a refinery. Evidently the charge on the earth under a storm cloud is distributed over these conductors and, when the cloud is discharged, surges travel along pipe lines and over wet ground toward the point where the lightning strikes. If this view is correct, towers, cables, and grids should be securely attached to tanks and to pipe lines on or near the surface. When a tower in this area receives a lightning discharge the charge on the earth's surface would collect principally on pipe lines and travel in a surge toward the tower.

A number of simple resistance measurements were made in the oil fields of Oklahoma, Texas, Louisiana and a number of places in California which indicated that the pipe lines were quite satisfactory for grounding lightning devices. In several locations resistance measurements were taken on the casing of water wells from 50 to 300 ft. deep. From these points it was established that pipe lines were well grounded and from the latter a number of tanks were found to make good contact with the earth. Although several hundred measurements have been made, in no case has it been found that the resistance of a pipe line to ground, or of a steel tank amounted to more than half an ohm.

It is sometimes considered necessary to sink a shaft 50 ft. or more, to permanent water, to establish a good ground for lightning towers. Surely this can do no harm, but it is doubtful if there is information which indicates that it is necessary.

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## Discussion

### LIGHTNING PROTECTION FOR OIL STORAGE TANKS AND RESERVOIRS

(SORENSEN, HAMILTON AND HAYWARD)

### LIGHTNING PROTECTION FOR OIL TANKS

(SCHAEFFER)

DEL MONTE, CAL., SEPTEMBER 16, 1927

**R. J. Reed:** I should like to say just a word regarding some field work in which six of the oil companies on the Coast have cooperated during the past summer. It seemed wise to erect, at a location where we might expect a great many lightning storms, several towers similar to those now protecting a number of oil reservoirs in Southern California. Carson Spur, a high ridge in the Sierras 25 mi. south of Lake Tahoe, was chosen. As soon as the snow was off the ground five steel towers were erected, instruments were installed, and observations were carried on during the summer. Near the towers small structures simulating reservoir roofs were constructed, but these were not protected with grounded conductor network as described in Dr. Schaeffer's paper. Unfortunately we have no results to report as there were practically no storms this year. We shall go on with these observations during another year with the hope that there may be lightning storms and that some of our towers will be struck.

With respect to the combination of direct-hit towers and grounded conductor network installed for protection of oil reservoirs as described by Dr. Schaeffer, we have had the following experience. At our Stewart Tank Farm, near Brea, California, during a severe lightning storm on December 8, 1926, two towers received direct hits. These towers were situated adjacent to 750,000-barrel reservoirs filled with light refining crude oil. The evidence of the direct hits is the report of eyewitnesses who were so stationed as to see the towers readily, and who state that one tower was struck and that within a few minutes the other tower received a direct hit. No damage was done either to the protective equipment or to the reservoirs. So far as I am aware this is the only field test of protective equipment of this type.

**M. E. Dice:** Sparks caused by induction seem to be responsible for more fires in the petroleum industry than direct strokes of lightning. It is not enough to protect oil-storage containers against direct hits; they must also be protected against secondary effects. The records of Dr. Schaeffer's adaptation of the Faraday cage in Louisiana indicate that it is meeting with success. Lightning towers erected in Southern California at the location of a disastrous fire in April 1926 were struck by lightning eight months later, at which time a combination of towers and networks prevented any damage to the remaining reservoirs.

Two conditions must be present if ignition is to occur by induction, the occurrence of a spark and the presence of flammable material. The authors of these papers have discussed chiefly the elimination of the spark. Let me emphasize the importance of preventing a flammable or explosive vapor in oil tanks. Practically all Pacific Coast petroleum companies have taken this precaution, accomplishing it by refining the crude oil formerly stored in earthen reservoirs, placing all volatile fractions in safe all-steel gauze-vented tanks, and returning only the heavy non-volatile fuel oil to the reservoirs. Where refinery capacities will not permit this, the oxygen content of the vapor above crude oil in reservoir is decreased by the constant addition of washed flue gases to the point where ignition is impossible. Sparks, however produced, are incapable of damage if there is nothing for them to ignite.

Professor Sorensen's paper mentions the effect of the insulating properties of oil in deflecting to the edge of the reservoir strokes which might otherwise hit the center. This applies only when the reservoir is not roofed or is covered with a dry non-conducting roof. If the roof is wet, as it is many times during thunderstorms, the oil is covered with a conducting sheet and the dielectric effect of the oil is decreased or nullified.

In the measurements of current discharged from sharp points, it is well to remember that the voltage gradients reported are the average gradients between the upper plate or "cloud" and the lower plate or "ground." The actual gradient at the tip of the needle is the one in which we are interested, and it could not be measured. The actual gradient at the point is considerably higher than the average.

Measurements of the electrostatic field distribution by electrolytic methods are valuable in many problems, but they fail when the field about a sharp point is to be mapped. The electro static and electrolytic fields are not the same in the immediate vicinity of a discharging point.

Table I should not be taken too seriously. It was quoted more or less at random as an example of many such tables and should not be used alone for the design of tower systems because the conditions of the tests reported were quite limited.

Close scrutiny of the table reveals serious differences due to changing the scale of operations. We were unable to eliminate scale differences but were reassured by the fact that as the scale increases or approaches full size, the degree of protection increases. Therefore we hope for as much as, if not more protection under actual lightning conditions then in the laboratory.

The summaries shown in Tables II and III are likewise affected by scale differences. The actual values shown have little meaning. They indicate only that various circuits give widely different results, or that laboratory lightning is not a standard article. Better protection was obtained when the surge generator was used than with other circuits. This is encouraging, because the surge generator is thought to be the best laboratory analogy of lightning now available.

The translation of laboratory lightning data into full-scale magnitudes has not been accomplished with any degree of certainty. It is to obtain full-scale data for this purpose that we have established an observatory which we call the "Camp of the Cooperating Competitors" in the High Sierras.

**E. H. Wilcox:** (By letter) The paper, "Lightning Protection for Oil Storage Tanks and Reservoirs" seems to indicate that the prevention of lightning by the establishment of proper convection discharge from ground to cloud is impossible. I am glad of the opportunity to offer the following for consideration:

Speaking of the proposal to prevent lightning discharge by prevention of the accumulation of sufficient charge on cloud and earth to cause a discharge between them, the author says:

"There are no known records of this having been accomplished . . . although there have been many schemes suggested."

He further states:

"If conduction current great enough could be obtained, there would be a possibility of keeping the potential between earth and clouds down to a value too low for the discharge by lightning." With this last statement we are in perfect accord, as it is in line with our own experimental conclusions, provided that he would consent to change the word *conduction current* to read *convection current*, inasmuch as the process by which this is accomplished is not conduction along a metal or other conductor, nor along a path that has been made conducting by reason of a lightning flash, which lightning flash itself has been made possible because of the intense localized and concentrated ionization which has created a conductive path between cloud and ground.

A convection current, on the other hand, does not create such a conducting path, but by reason of its distribution in space prevents such local concentration of ionization as to cause conduction.

The experiment, as shown in Fig. 5, is practically a duplication of one of the earliest of our own experiments, but as we soon learned, has no relation to the question of how much current can be dissipated by convection on a properly designed system.

Were it proposed to afford protection by setting a few points over a reservoir or tank, insulating each point from the roof of that tank, then there would be some reason for this experiment. As far as I know, no one has ever proposed such a method of protection, although Von Diest in his suggested method approximates this most closely, but it is one that does not interest us. Our experiments on this line were that we might perfect a chain of investigation rather than as an end in itself, although we did carry it to the point of experimenting with up to 1000 points in a shielded field.

Here our results come into approximate alinement with those shown in Fig. 7, if he will change the word "conduction current" on the left-hand margin to read "convection current."

Study of the curves and tabulation in Fig. 7 shows that all the author's experiments maintained a constant ratio in the variables of the set-up:

| | Cloud ht. in. | Point ht. in. | Point spacing in. | Current flow microamperes per point |
|---|---|---|---|---|
| 1.......... | 12 | 1.0 | 4 | 4.7 |
| 2.......... | 6 | 0.5 | 2 | 1.6 |
| 3.......... | 3 | 0.25 | 1 | 0.2 |

and yet that the current flow increased with dimensions as shown above in the final column, at corresponding gradients (80 kv. per ft.). Here he has the whole matter in his hands, but throws it away. He says "but it is inconceivable that the same order of increase of current with increase of scale will be maintained up to the scale of clouds and lightning towers in actual use." We should like to say "Why?"—especially as the curve is still a rising one and shows no suggestion of flattening out.

We would suggest that the speaker carry out extension experiments using the same ratio of cloud height, point height, and spacing and increasing the cloud height say by steps to 144 in. all at a gradient of 80 kv. per ft., and then note the curve of current flow. Then as a variant he might change the spacing of the points and note the results. Of course to do this he would probably have to use alternating current, but the charging and capacity components of the observed flow can be extracted vectorially, leaving only the convection discharge.

In spite of this, for a reason which he does not explain he elects to use an arbitrary figure of 2.5 microamperes per point in certain calculations. He also seems to feel that his spacing of points at four times their height is the ideal although, as he shows on the sixth page, second column, no absolute protection exists even within the 1-1 ratio.

In view of his limited experiments and the concession that his calculations may be largely in error it scarcely seems worth the while to discuss his computations on the fifth page. As a reduction *ad absurdum*, had he assumed a 6000-ft. cloud he would have asked for the same number of towers but 500 ft. in height and 2000 ft. apart; or with a 24,000-ft. cloud, towers 2000 ft. high and 8000 ft. apart, denying by inference that any intermediate towers or points would have an amelioriating effect.

One question, however, we should like to ask, in view of his computation, that 2,500,000 towers are required to afford protection: Was the speaker correctly quoted in the press reports of January 10th (United News Leased Wires) in which he was credited with recommending: "an extreme lightning rod consisting of 150 to 175 towers placed near the tanks to be protected?"

I find that to rearrange the points shown on Fig. 5 into a peripheral ring instead of concentrating them in a massed position in the center of the field raises the current as dissipated by convection many times, and also that the overcrowding of points, even into a peripheral field results in a diminution of total current. This particular line of investigation was not carried to great lengths, as it was only a connecting link between the dissipation from such a shielded point as referred to by the author, and points arranged on a closed cordon of wires.

On such a cordon which is representative of the protection system as actually adopted, we find the dissipation of convection current *per point* varies with the potential gradient of the field, the number of wires in the field, and the length and spacing of points on the carrier wires.

The following table will show the results of one experiment. In this 12 points were arranged on a single ring 30 in. in diameter, or approximately 7.85 in. apart, and the potential gradient raised to values shown below, with the following convection current discharge per point:

| Potential gradient in volts per cm. | Total convection current in microamperes | Flow per point in microamperes |
|---|---|---|
| 494 | 3.2 | 0.27 |
| 614 | 9.8 | 0.81 |
| 770 | 32.0 | 2.66 |
| 985 | 68.0 | 5.65 |
| 1360 | 153.0 | 12.7 |
| 1650 | 222.0 | 18.5 |
| 1970 | 480.0 | 40.0 |

These were all with direct current, neither pulsating nor rectified. The final gradient is considerably less than one-half the danger gradient. From a study of the above it is evident that a figure in excess of 100 microamperes per point would have been reached before approaching the danger zone.

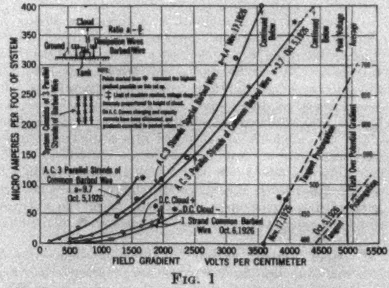

Fig. 1

In another experiment with a single point in the field, in a gradient of 80 kv. per ft., a discharge of 780 microamperes was recorded.

Fig. 1 herewith shows the actual dissipation or convection current as measured for a one-wire and for a three-wire system. Our opinion is that the form and spacings of points on the wire and the method of attachment of points is of considerable importance, but we have not sought to follow this in detail experimentally, simply selecting the longest and sharpest points obtainable and specifying that points should be welded to the carrier wire, or that the wire be regalvanized after assembly of points.

It will be noted that on curve $a = 4.4$, November 17, 1926, actual convection currents to the value of 475 microamperes per lineal foot of system were measured; a tangent prolongation of this curve to the flashover value promises that over 650 microamperes per foot may be expected.

A comparison of curves $a = 9.7$ and $a = 3.7$ October 5, 1926, with the ascending curve of discharge as recorded by Professor Sorensen on his Fig. 7, confirms our opinion that the scale may be a very important factor, and suggests that actual discharge may reach a much higher value than any recorded in the laboratory.

We further find that the total current flow with 12 points arranged in 3 close groups of four is practically identical with that from 3 single points, indicating that arrangement and spacing, rather than number, is the important thing.

In all our experiments we were compelled to work at comparatively low gradients, as we did not wish to risk the danger of a flashover which might have been ruinous to the microammeters in use, hence this limitation.

It soon became apparent that the intelligent unit to use in any such investigation is not the value per point, but the value per lineal unit, for any given spacing. Further experiments, however, showed that there was comparatively little difference in the totality of convection current from a given system, whether there were two, three, four, or five wires in that system, provided that the over-all spacing between wires 1 and 5 remain constant. Or in other words, removing wires 2 and 4 from a 5-wire system only raised the unit value per wire, the totality at a given gradient remaining practically constant. An increase in the spread of the wires resulted in an increase in totality. A decrease of spread reduced the totality. This is by reason of a partial interference of the convection currents from the several wires.

Theoretically, I believe that as good practical results could be achieved on a well designed two-wire system as on one with multiple strands, although the multiple system has the advantage of giving rather lower gradients in the immediate vicinity of the points, and insures that the mechanical breaking of a single wire does not affect it unduly.

The assumption of the author seemed to be that the entire charge of the cloud should be discharged to effect protection. This is not our conception. A discharge that will balance the charging rate of a cloud, or even a discharge that will balance the charging rate for the last portion of discharging period, is all that is necessary to prevent the potential gradient reaching the flashover point. It takes only a small relief valve on a boiler to prevent its blowing up, even though the fires be not drawn.

Table I is interesting and certainly affords food for thought. One question immediately suggests itself. With the center of cloud discharge vertically over a point which is four tower heights away from the tower, why should there be any discharges within a circle of 1 or 2 tower heights from the tower? The remarkable part of this experiment is the number of strokes that fell within these circles in spite of the set-up. How any strokes at all fell within this zone with the additional protection of a tower, only shows the vagaries of lightning discharge.

We accept without reservation his conclusion:

"Results of the tests made for all types of discharge used show no absolute immunity for any area around a rod."

We are not able to accept equally his statement:

"Considered from a statistical viewpoint, the number of hits within a circle having one rod height as a radius and with its center at the rod was practically nil"

in view of his succeeding clause:

"But there was an occasional hit even within this area which was not taken by the rod.

His experiments here were scarcely sufficiently numerous for so broad a generalization."

I should, however, point out the essential difference from an oil man's standpoint in the attitude regarding the percentage of protection. Granted that 99 strokes out of 100 in a given case might be taken by the towers, and only 1 taken by the protected object, yet that does not mean a 99 per cent protection. It means 100 per cent risk, as we have only to wait for 100 discharges to have occurred before disaster will have overtaken us, but we have no assurance whether it will be the first or the 50th, or the 99th stroke that will do the damage. To a statistician the protection may be 99 per cent; to an oil man it is zero.

All the thought of the speaker seems to be toward averting direct strokes. No well informed man questions that this can be done in very large measure by any intelligent tower system. Oil men know, however, that the majority of oil-field and oil-tank lightning fires are not caused by direct strokes at all, but by secondary discharges, due to the release of the hitherto bound charges simultaneously with the primary discharge.

No system of rods or towers affords or even pretends to afford protection from these dangerous secondaries.

All oil companies today endeavor to limit these hazards by the avoidance of explosive or inflammable mixtures in or around tanks to lessen this danger. Some of the methods used are expensive, both in installation and maintenance, and may fail at the needed time.

We have experimented in many ways to find a method of controlling these secondaries in the presence of primary; frankly they are all failures. Our deliberate judgment is that the only certain protection against secondaries is to prevent the occurrence of primaries.

**S. S. MacKeown:** I want to point out a very interesting bearing that the paper by Professor Carroll and Mr. Lusignan[3] has on the matter of preventing lightning by discharge from points. Professor Carroll pointed out in the discussion that where he was using a rectifying d-c. voltage the peak of his current came approximately a quarter of a cycle after the peak of his voltage. That is, it took approximately a quarter of a cycle for the current to move from the wire out to a cylinder. The distance from wire to the cylinder was 7½ in.

If then we did assume that a sufficient discharge was dissipated from points to neutralize a cloud, that charge would travel to the cloud with a very limited velocity. The velocity is very readily obtained from the work of Mr. Carroll. It differs for different potential gradients; but if we take the value for 42 kv.—given on his Fig. 9,—we find it takes a quarter of a cycle to travel 7½ in.; that is, about 150 ft. a sec.

Now, the average distance of a lightning cloud is about 2400 ft.. and average rate of time to charge up is about 10 sec. If then we assume that these ions travel with this same velocity from the points up to the cloud, they would not reach the cloud in time to prevent a lightning discharge.

When you consider also that the cloud is usually moving at a fairly large velocity due to wind, if the charge should reach the cloud, it would reach it at some point other than over the district sought to be protected.

**J. T. Lusignan, Jr.:** In the work carried out at Stanford University last year a rectified space charge was found to be built up in the ionization process about a point in a-c. corona. With a point in a unidirectional field, as that of a rod below a thunder cloud, this effect would be more marked, as a copious supply of ions of one sign would surround the point when the field intensity becomes sufficient there to start ionization. This "cloud" of ions would tend to shield the point and reduce the field intensity there in such a way as to cut off materially the supply of ions that, with the cage system of lightning protection, must go up to the thunder cloud of opposite polarity to discharge it.

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[3] *The Space Charge that Surrounds a Conductor in Corona*, J. S. Carroll and J. T. Lusignan, Jr., p. 50.

Mr. Dice made a very apt comment on the need for care in applying to the field the results of laboratory studies of protective arrangements and reduction of cloud charges by points. It must be remembered that although the heights of the cloud and rods, and the size of the tanks may all be brought down to scale, the ion used in the laboratory is the same ion that is involved in the lightning stroke, and its size and velocity cannot be brought down to scale. Accordingly, it is problematical how closely its behaviour and path in the laboratory follow those out under a cloud. It would seem obvious on the other hand that the larger the laboratory set-ups, the nearer conditions in practise would be approached, a fact which Peek has seemed to realize fully in his endeavor to use as large laboratory models as possible.

**H. P. Miller, Jr.:** (communicated after adjournment) There is a marked similarity between the design of protective networks for oil-storage tanks and the design of ground systems for high-power transmitting antennas. A storage tank is screened so that if it is struck by lightning the steep-wave-front impulse is led off to ground through a low-resistance path. An antenna ground system provides low-resistance paths for radio-frequency currents going into the ground plate of the antenna, which is simply a large radiating condenser. Many of the same design considerations will therefore apply in both cases.

In a transmitting antenna the ground system is designed so as to minimize the impedance of conducting paths from all parts of the ground to the radio transmitter. Using conductors of low resistance is not always sufficient since their reactance may be so high as to force the currents off through some medium of high resistance. It is therefore desirable to use direct leads from a large number of widely scattered ground points to the transmitter. Applying these principles to the protection of an oil-storage tank would mean the use of conductors from the center of the tank to a large number of buried connections around the outside of the tank.

The method described by Mr. Schaeffer for protecting steel tank meets these requirements except for the ground connections around the outside. The use of such an arrangement might not be economical but would help considerably in keeping the strong field away from the edges of the tank where fires are so likely to start.

Mr. Dice has called attention to the fact that the laboratory investigations with a salt bath give the electrolytic field and not the electrostatic field. From a study made by the writer in connection with the insulation of guyed masts[4] it would appear necessary to map the electrostatic field by means of a convenient sized model.

**R. W. Sorensen:** I am sorry Mr. Wilcox is not here to present his discussion in person for I should like to have him explain how he made the tests upon which he bases his proof that our results are absurd. Inasmuch as we cannot have that presentation I fail to see the advantage in taking up valuable time to defend each detail of our paper which for some reason Colonel Wilcox has seen fit to attempt to disprove, and I will make no defense of our work other than to say that, though we know it is incomplete, we have to date found no disagreement with the results we have presented and results which have been obtained by other engineers experienced in conducting high-voltage experiments.

The work which we have reported and which was done at California Institute of Technology was made possible only by the cooperation of the oil companies, who contributed the cost of the work, and the engineers of these companies who assisted in doing that work. For their cooperation and that assistance we are indeed most grateful, but we hope that means will be provided so that this work may be continued until such results which have been presented are checked and further data have been obtained.

The object of the program which formed the basis of this paper was not the development of some commercial project to be sold to oil companies for financial gain, but was purely a scientific project to enable the oil companies to obtain protection in every way possible and to further the scientific knowledge as to the performance and character of lightning. In presenting this paper we have wished to bring out for discussion certain facts learned to date and in this we think we have been fairly successful.

Secondly, it is our desire to encourage more groups of people working in high-voltage laboratories to take up the problem because we think definite results will be obtained more rapidly if the problem can be attacked by several groups who do their work at different places; in fact, we are convinced that if a number of groups had attacked the problem sooner there would be more knowledge and agreement as to the exact character of the phenomena.

We also feel certain, as a result of this work, that we can now analyze places to be protected and devise systems of towers and overhead networks used alone or in combination which will give a very large degree of protection, the amount of protecting obtained being entirely a question of economics. In doing this, however, we are also quite certain that no means can be provided which will be very successful in a lightning district in preventing the occurrence of strokes, (of course there are others who differ from this and we seem to have two authentic records—one of my correspondents has told me that a tall smelter keeps away lightning because there has been no lightning within five miles of the stack, and we found that the towers which were erected at Carson Spur this summer have been so effective that the three or four towers have kept all lightning from occurring in the High Sierras during the summer). There were also rumors and reports in the press that a barbed wire entanglement erected in France had kept away lightning strokes. At my request Dr. John Whitehead, of Johns Hopkins University, investigated the report as to this protection while in France and informs me he can find no record of its having been successful or even of its having been tried out to any great extent. I think, therefore, we have sufficient basis for our statement that lightning strokes cannot be prevented by the erection of a barbed wire fence, even if the barbs are large.

In conclusion, therefore, may I point out that protection can be obtained, first, by having all inflammable materials completely caged in all-metal tanks; if tanks which are not all-metal are used, only heavy non-inflammable residuum fuel oils should be stored therein, and if lightning may occur near such oils these reservoirs should be guarded by towers approximately 200 ft. high and so spaced that the distance between towers is not more than five tower heights, the tower height being the height of the tower above the top of the object to be protected.

Of course the supreme method of protection has not been mentioned; that is, keep the oil in the ground until needed. This, of course, can only be done when some method is developed which will enable the oil companies to control production. There is no danger of oil in the ground being ignited by lightning stroke.

We have considered carefully all the points mentioned as to scale effect, and we have drawn our conclusions with full knowledge of the limitations of our work due to that effect.

Another point is, we find that on the Pacific Coast we should be very grateful for our freedom from more frequent lightning strokes. One place I visited in the East this summer had the lights go off twelve times in one afternoon because lightning interfered with the transmission lines. In districts where lightning is as prevalent as that it is easy to understand why some power companies are talking of extending all towers well above the transmission lines and stringing a number of ground conductors for the sole purpose of obtaining protection against lightning.

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[4] "The Insulation of a Guyed Mast", by H. P. Miller, Jr., *Proceedings* Institute of Radio Engineers, March, 1927.

In conclusion may I say that the problem is still wide open and the more groups interested in it, particularly in our colleges, the better. In order, however, to bring about this condition, the college groups will need assistance in financing their work by the industries interested in obtaining protection.

**C. D. Hayward:** The phenomenon of the conduction of electricity through gases by means of ions is one which has been known and studied for many years. The idea of applying this phenomenon to the prevention of lightning is also not new. There is at least one case on record where it was tried in France a few years ago using a grounded system of barbed wire similar to that proposed by Mr. Wilcox. This system was later abandoned, probably because of failure.

Granting that conduction of electricity through gases is a different phenomenon from conduction through metals, and granting that the flow of currents from pointed conductors through a gas differs from an arc or spark discharge in that in the former case the gradient is high enough to cause ionization by collision only in the immediate neighborhood of the pointed conductor while in the latter case ionization occurs along the whole path of the discharge, still the use of the term "conduction" to cover all these has become established by usage in physics and I doubt if it would be possible to change the term to "convection" now even if it were desirable to do so.

Near the beginning of his discussion Mr. Wilcox makes the statement: "Were it proposed to afford protection by setting a few points over a reservoir or tank, insulating each point from the roof of that tank, then there would be some reason for this experiment." Mr. Wilcox does not seem to understand that the needles and the ground plate were at the same potential since the needles were connected to the plate through the low-resistance micro-ammeter as may be seen by examining our Fig. 5. The only reason for insulating the needles at the point where they pass through the ground plate was to cause the current flowing off the points to pass through the micro-ammeter.

Mr. Wilcox has not given enough data on the dimensions of his apparatus to enable anyone to compare the results given in his discussion with those given in our paper. He does not give the height of the 12 points mounted on the 30-in. ring nor does he give the height of the cloud electrode above the points. He does not give the shape of his cloud electrode nor does he tell whether or not he used a grounded plate under the 30-in. circle to represent the earth surface. It will immediately be apparent to anyone familiar with electrostatic fields that these factors will affect the potential gradient in the air near the points not simply a matter of a few per cent but several hundred per cent. Since the potential gradient is what determines the current flow it is easy to see how Mr. Wilcox might be able to get large currents from the points by using certain extreme forms of apparatus. Data of this kind are useless because these extreme forms of apparatus cannot be duplicated in the field. We cannot change the shapes of the clouds and the earth to suit our fancy. When making the tests described in our paper, we made the proportions of the model such that they could be duplicated in the field. Assuming a 2400-ft. cloud, which is a good average for the height of storm clouds, the points would be 200 ft. high, which is about the maximum height that towers can be erected without too great an expense. We placed the points at a distance of four times their height apart because we found from a study of the electrostatic fields that this was as close as we could place them without having the gradient in the air near each point greatly reduced due to the electrostatic shielding effect of neighboring points. It is of course necessary to keep this gradient as high as possible in order to obtain the maximum current flow from each point.

Near the end of his discussion Mr. Wilcox gives what to his mind is a difference between the attitudes of an oil man and a statistician regarding the percentage of protection afforded by a given protective scheme. He says that to an oil man no protective scheme gives any protection unless it gives 100 per cent protection. This seems to me to be a very peculiar attitude, because reducing a risk in the ratio of 1 to 100 certainly means something to an engineer, and most of the men holding the higher positions in the oil companies are good engineers.

# 132,000-Volt, Single-Conductor, Lead Covered Cable

## Introduction, Economics and Commercial Demand

BY P. TORCHIO[1]
Fellow, A. I. E. E.

***Synopsis.***—*This paper, which describes the development of the oil-filled type of 132,000-volt cable, has for convenience been divided into four parts.*

*In the first part the economic and commercial aspects of the development are discussed. It is pointed out that this type of cable permits direct interconnection with high-voltage overhead lines and it is felt that the satisfactory operation of the two lines which have been placed in service this year will be an indication that 220,000-volt cable can be constructed without material changes in the design.*

*The theory and design of the cable are completely developed in the second part. Particular reference is made to the effect on the dielectric of occluded gas and the method of eliminating trouble from this source in the oil filled type is described.*

*The third part relates to the manufacture, inspection, and testing of the cable and equipment. The tests showed that the electrical constants of the cable were substantially unchanged by the normal temperature cycle.*

*The installations at New York and Chicago are described in the fourth part. Inspection, indication of oil leaks, cable and joint repairs are discussed. The replacement of a length of the New York cable, which developed a leak in the sheath, is covered in detail.*

* * * * *

WHILE the power generated from local plants in heavy centers of industry and population is distributed locally at about 13,000 or 25,000 volts, system interconnection lines and long-distance transmission lines require considerably higher pressures in the order of 66,000, 132,000, and 220,000 volts.

In most situations of heavily built-up centers, it has been impossible in the past to tie the higher voltage lines directly to the distributing stations and substations, and recourse has been made to underground cable lines of 33,000, 45,000, and 66,000 volts connecting to the higher voltage overhead lines through transformers located at substations on the outskirts of the city. One of the principal aims of the design of the new type of cable, which by one step doubles the highest underground operating voltage used heretofore, is to do away with these outside intermediate substations by bringing the higher voltages directly to the ultimate distributing centers. The economic and operating advantages thereby obtainable are savings of intermediate substations, transformers, switchgear and attendance, reduction in number of underground cables, savings in synchronous condensers, increased efficiency, improved regulation, and improved stability of parallel operation of local plants with the outside sources of power. The final relative values of these savings will not be available until we have secured from actual experience the relative carrying capacity of the oil-filled cables in contrast with the ordinary type of cables with solid insulation.

The theory of the oil-filled cable is that through its collapsible oil reservoirs it responds readily to volumetric changes in oil and cable due to temperature changes. In this manner, the whole cable is kept constantly filled with oil under pressure both in the hollow core of the conductor and throughout the surrounding insulation. The unique advantage of this type of construction, therefore, is that should the lead sheath be expanded or distorted, or the internal elements of the cable be displaced by temperature variation or other causes, the spaces thus formed will be immediately filled with oil, while in a solid insulation type voids would be formed, causing ionization and ultimate failure. It is thus evident that this new type of cable should be able to operate safely over a much larger range of copper temperature and therefore of load, than a solid insulation type, even if the latter is operated only at 66,000 volts or less. In this expectation we are confirmed by the original installation of this type of cable made in Italy three years ago, which consisted of about 2000 ft. of line connected in series with a 130,000-volt overhead transmission line more than 100 mi. long. This cable, which was 50 sq. mm., about 100,000 cir. mils, in cross-section, has never given the slightest trouble though carrying currents of 250 amperes per phase, a current density which would be absolutely impossible with the solid type of cable even if operated at 25,000 volts or less.

The Chicago 132,000-volt underground cable line is a direct application of the plan of connecting a generating plant in the city to an outside 132,000-volt line six miles away.

The New York 132,000-volt cable is, for the time being, a large capacity, 12-mi. length transmission line supplying the large county of Westchester in the state of New York, but it will in future serve also to interconnect with outside sources of power supply.

The Chicago and New York installations were placed in operation, respectively, on June 2nd and August 9th, of this year, and have since operated without electrical trouble.

The manufacturers feel that should these two 132,000-volt cable lines continue to prove satisfactory in opera-

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[1] The New York Edison Company.

*Presented at the Regional Meeting of District No. 5 of the A. I. E. E., Chicago, Ill., November 28-30, 1927.*

tion, 220,000-volt cable can be constructed without material changes in the design of cable, joints, and accessories.

The next year's experience of the large New York and Chicago installations appears now almost certain to prove satisfactory, in which event this great advancement in the art will have made available to the industry, confronted with unprecedented volume of growth in its demand for power, means not heretofore available for transmitting hundreds of thousands of kilowatts economically and directly to and from centers of heavy population and outside supervoltage overhead lines.

In the following chapters the manufacturers and the users are presenting a complete description of all the phases of work involved in the design, manufacture, and installation of this radically novel type of cable.

## Theory, Design and Development of the 132,000-Volt Cable

BY L. EMANUELI[2]*

Non-member

*General.* It is well known and recognized that one of the principal reasons of failure in high-tension cables is the presence of gas bubbles and films in the dielectric, some of these gas occlusions being left in the insulation during the construction of the cable and some being formed later during the operation of the line.

This is due to many facts. First, the vacuum applied to the cable before impregnating it with insulating compound is not generally perfect. Second, the insulating compound carries in solution a great volume of gas, part of which is set free while the compound is passing through the paper during impregnation. Third when the lead sheath is applied to the cable, the cable is still rather warm and the subsequent thermic contraction of the compound when the cable cools down causes further voids. Empty spaces are also created when the cable is coiled on the reels and during handling.

When the cable is in operation, another important phenomenon takes place. The insulating compound is warmed up and increases in volume when the cable is loaded and this first compresses the gas in the dielectric and then expands the lead sheath. As the lead is more viscous than elastic, after a subsequent cooling the total amount of void space within the dielectric is greater than before installation by an amount proportional to the load carried.

For example, in a 66,000-volt cable, the contraction which follows an increase of temperature in the copper of 35 deg. cent. causes a volume of seven gal. per mi., (16 liters per km.) to be emptied of compound.

The pressure which may take place in a cable when loaded, and which forces out the lead tube, has been found by actual measurement to be in the neighborhood of 90 lb. per sq. in.

Seasonal temperature variations produce the same effects.

Where is it that these empty spaces are formed? In a general way, we can assume that they are produced at the points where the paper is less compact, in the wrinkles, in the space between the lead and the insulation, especially where the lead is expanded due to bends or handling and, for three-conductor cables, in the spaces between the insulated conductors and the fillers.

This may be explained when one thinks that the surface tension of the compound has a tendency to fill up first the smaller cavities, thus leaving empty the larger ones.

In addition to this, the compound has a tendency to migrate to the lowest points of the cable and this migration is greater the lower the viscosity of the compound.

This irregularity in the distribution of the gas cavities is one of the principal causes of the many uncertainties in the results obtained in the laboratory and during operation, and makes it impossible to fix an exact figure for the permissible value of the ionization as a function of the working voltage.

The failure of all the previous attempts made to explain theoretically the breakdown voltage on a sample of cable, in connection with the electric gradient in the insulation, can probably be attributed to the presence of gas occlusions and to their irregular distributions, and perhaps the theory which gives the breakdown voltage as a function of the minimum gradient and not of the maximum, is not to be completely discarded, the minimum gradient being near the lead where the empty spaces, at least for a single-conductor cable, have a greater tendency to be formed.

If the empty spaces due to the thermic contraction of the compound were formed uniformly in the insulation, in small units, the troubles produced by their ionization would be very small. A step toward this point has been gained by the cable manufacturers by wrapping the paper on the conductors as uniformly as possible, and avoiding wrinkles and registration of the layers.

It is also evident that the greater the thickness of the insulation, the smaller is the possibility of avoiding such empty spaces during construction. In addition to this, if the contraction of the insulating compound should be such as to distribute uniformly and in small units the empty spaces which are formed, then the quality of a dielectric would be independent of its thickness; but, due to their localized formation as a consequence of capillarity and drainage, the probability of leaving big empty spaces is greater the greater the volume of the dielectric, and accordingly of the amount of oil subject to volumetric change. We can assume, therefore, that an increase in the insulation thickness does not produce a corresponding improvement in operating performance; and the cable manufacturers know this very well.

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[2] Società Italiana Pirelli.

*Acknowledgment and thanks are made here to Dr. E. Sacchetto who has given his assistance in the first experiments on the oil filled cable and in the installation of the Brugherio cable, Mr. E. Sesini who has assisted in the theoretical design of the cable and accessories, and Mr. M. Puritz who, with Mr. Sesini, has directed all the delicate operations of installation and impregnation of both the New York and Chicago lines. Acknowledgment is also made of the valuable assistance and cooperation rendered by the engineers of the General Electric Company and of the New York and Chicago Companies during all these latter operations.

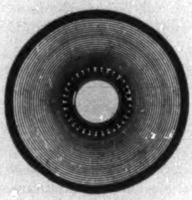

FIG. 1—HOLLOW CORE CABLE

All these difficulties and uncertainties would not have allowed the design of a 132,000-volt cable of the usual type with any probability of success and the results which may have been obtained in the laboratory and in the field on short lengths of cable would have been practically worthless due to variations in the distribution of the gas occlusions.

It must also be considered that the experience gained on a large scale on existing cables is limited to a voltage which is only about one-half of 132,000 volts. It was with the idea of avoiding all these uncertainties, eliminating gas occlusions as much as possible and especially the ones which are formed by temperature variations, that the writer designed and carried out the construction of the oil-filled type of cable.

The principle is very simple and consists in having the cable connected to a reservoir which will receive the oil pushed out during the thermic expansion and give it back to the cable during the contraction. To obtain this action, it is necessary to have inside the cable a passage which connects the reservoir with every point of the dielectric. This feature can be obtained readily by stranding the copper wires of the conductor around a metal spiral, thus leaving a single central passage, see Fig. 1, or by shaping the lead sheath as shown in Fig. 2, thus making several longitudinal paths which can be connected to the reservoir. This eliminates the danger of formation of empty spaces due to the contraction of the oil.

The presence of a longitudinal path makes possible the evacuation and impregnation of the cable from both ends after it has been leaded. On account of its small volume, laboratory pumps can be used and a very high vacuum reached. In addition to this, a special process has been worked out to purify the oil from the gases in solution, before impregnating the paper.

In this way it is possible to obtain a cable practically without any occluded gas from the start and also to maintain it in such condition during operation.

An experiment on a cable of the type given in Fig. 1 was made early in 1918 and the results were quite surprising. The life tests gave results far better than those on usual cables and it appeared immediately that the importance of a perfect construction of the cable as referred to wrinkles and compactness of the paper could be regarded as secondary.

It is important to remember that in a cable made in the usual way, the breakdown voltage is very high if the voltage is increased quickly and does not give any light on the punctures which happen in operation at a voltage generally equal to, or slightly higher than, the operating voltage. If the tension is applied for several hours, the breakdown voltage is considerably smaller, and the longer the time of the test, the lower the breakdown voltage. It is not difficult, for instance, to get a breakdown voltage on a short sample, after a few seconds, which is five times greater than that found after several hours of application of voltage.

In the oil-filled cable these differences were found to be much smaller, and as the instantaneous breakdown voltage is equal to, if not greater than, that on usual cables, the breakdown voltage after several hours is more than doubled. This permits increasing the operating gradient of the cable and the use of only a small thickness of insulation.

Another advantage over other cables of the usual type is to have much smaller dielectric losses at high temperatures because it is possible to use a very fluid oil with very small power factor, as the danger of migration of the compound is avoided.

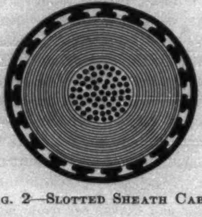

FIG. 2—SLOTTED SHEATH CABLE

For several reasons a field test of this new type of cable was not made on a large scale until the end of 1923 when a line of three cables of 100,000-cir. mil (50-sq. mm.) copper area, 670-mil (17-mm.) insulation, each 2000 ft. (610 m.) long, with six joints, was installed at Brugherio near Milan, Italy, connected to an overhead line about 100 mi. (160 km.) long. In the beginning the cables did not carry load, but in 1924 they were put in series with the line and a load up to 250 amperes per phase was carried without any trouble for two and one-half years.

The electrical problem of the construction of a cable for 132,000 volts was in this way solved quite satisfactorily but several mechanical problems, especially complicated for lines of long length and with large differences of level, remained to be studied.

*Mechanical Design of the Line.* The first problem was to determine the most suitable dimension to be given to the hollow central passage as related to the viscosity of the oil and to the length and profile of the line. The oil which must flow from the feeding reservoirs to the various points of the cables is subjected on its way to friction and, if the distances are not properly calculated, an excessive pressure may take place in the cable when applying a sudden load, or empty spaces may be created for a short time, during cooling.

Let us consider first the problem of the cable which cools down and let us call $a$ the quantity of oil which, at a certain moment, the cable absorbs per unit of length (centimeter) and per second. Calling $q$ the flow of oil along the central passage and $x$ the distance of the point from the end connected with the reservoir, we have

$$a = -\frac{d\,q}{d\,x}$$

and then

$$q = -a\,x + q_0$$

Calling $l$ the total length of the cable, the flow of oil at the end opposite to the feeding end ($x = l$) will be zero and we have

$$q = a\,(l - x) \qquad (1)$$

Let us assume that the friction of the oil in its movement along the tube is proportional to the flow, which can be considered as true for very slow movements.

Calling $b$ the coefficient of friction corresponding to the shape of the central passage and to the viscosity of the oil, we have the drop of pressure, $d\,p$, on a length of core $d\,x$,

$$\frac{d\,p}{d\,x} = b\,q \qquad (2)$$

and from (1)

$$\frac{d\,p}{d\,x} = -a\,b\,(l - x)$$

Integrating,

$$p = -a\,b\left(l\,x - \frac{1}{2}\,x^2\right) + p_0$$

where $p_0$ is the pressure at the feeding end of the line, this formula being true only for a perfectly flat profile cable.

If the cable is not on a level, calling $h_x$ the difference of level between the point $x$ and the feeding end of the cable, ($h$ being positive if the point $x$ is lower than the feeding end) and $\gamma$ the specific density of the oil, we have

$$p = h_x\,\gamma + p_0 - a\,b\left(l\,x - \frac{1}{2}\,x^2\right)$$

For practical purposes, it is better to express $p$ in units of length of the oil head which let us call $h$ and $h_0$ the value corresponding to $p_0$. We have, then,

$$h = h_x + h_0 - \frac{a\,b}{\gamma}\left(l\,x - \frac{1}{2}\,x^2\right) \qquad (3)$$

It can be seen readily, applying the formula (3) with different values of $a$ and $b$ corresponding to various dimensions of the central core and oils of different viscosities, that it is not possible to feed long lengths of cable from a single feeding point because the pressure in the distant portions of the cable would drop so much as to create a vacuum inside the core and the dielectric.

For this reason it is necessary to divide the cable into a certain number of sections, each separately fed, stopping the passage of oil between them. The length of a section to be fed from one point has been determined graphically from the formula (3) assuming that the oil pressure during the cooling period should never be allowed to drop in any point of the cable below a certain figure, and this value was fixed to be the atmospheric pressure, $h = 0$.

The formula (3) for $h = 0$ and $x = l$ becomes

$$h_x + h_0 = \frac{a\,b}{2\,\gamma}\,x^2 \qquad (4)$$

In this expression, the quantity $\frac{a\,b}{2\,\gamma}\,x^2$, which we will call $H$, gives the drop of pressure, in units of length of the head of oil which takes place along a length $X$ from the feeding end.

Let us take the profile $A\ B\ C$ of the line, Fig. 3, on a certain scale, $X$ being the lengths and $H$ the elevations, and plot to the same scale the curve 1, $H_1 = \frac{a\,b}{2\,\gamma}\,x^2$, which gives the drop in pressure, the center of the coordinates corresponding to the center of the feeding reservoir $F$, and the positive direction being downwards. The curve of the profile of the line $C\ B\ A$ gives the static pressure of the oil at any point referred to the atmospheric pressure in units of head of oil, when the oil is supposed not to move.

The point $A$ at the distance $X_a$ where the curve 1 cuts the profile of the line, determines the length of a section, for at this point we have the dynamic drop of pressure equal to the static head.

It is necessary, however, to be sure that this condition is repeated for every point of the section. Taking $h = 0, l = x_a, h_x + h_0 = H_a$, the formula (3) becomes

$$H_a = \frac{a\,b}{2\,\gamma}\,x_a^2\left\{2\,\frac{x}{x_a} - \left(\frac{x}{x_a}\right)^2\right\} \qquad (5)$$

which gives the drop in pressure in every point of the section of a length $l = x_a$.

Curve 2, passing through $F$ and $A$, is plotted from this formula and the pressure of oil in any point of the cable during the cooling period is readily obtained as the difference between this curve and the one of the profile of the section. For instance, in Fig. 3 the pressure of oil along $B\,A$, (shaded area) would drop below atmospheric.

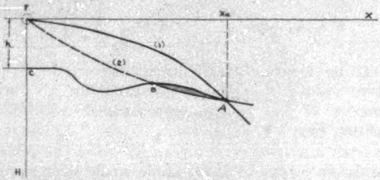

Fig. 3—Static Pressure Diagram with Feeding Tank Only

In the preliminary study of the line, the lengths of all the sections were determined from the curve 1, taking into account the position where the feeding point could be located on the ground, and also that the pressure in a section, under equilibrium conditions, should not be more than a certain value.

Curves similar to curve 2 were plotted for each of the sections, thus determining the portions of the section where, due to the profile of the ground, the pressure would be below the prescribed value.

For these portions, where possible, the profile of the conduit was changed by increasing the depth of the duct bank. In some instances, this was not possible and the length of the section had to be shortened.

In some other instances, however, practical considerations did not permit cutting down the length of the sections to the value calculated from the curve 1, and it was therefore necessary to give to the section an extra length. Evidently the part of the section beyond the point $A$ of curve 1 will not comply with the prescribed pressure conditions. In such cases, it was necessary to install a second supply of oil at the lower end of the section. This was done by means of special oil tanks, called pressure tanks.

The pressure tank consists of a strong metal tank full of oil, which has inside a certain number of air-tight cells, with collapsible walls, full of gas. The tank is connected with the lower end of the cable and for this reason the oil in it and the gas inside the cells are subjected to the pressure corresponding to the static head of oil from the reservoir.

When the cable cools down, the pressure at the far end of the section drops below the static head and the gas enclosed in the collapsible cells increases in volume, and pushes out the oil from the tank into the cable.

In Fig. 4, $F$ is the feeding point, $C\,A$ is the maximum length of cable which can be fed from $F$, determined as explained above, and $P$ is a pressure tank.

With these conditions, the section is fed from both ends, having the feeding tank at one end and the pressure tank at the other. At the first moment of cooling, the pressure tank is subjected to a hydrostatic pressure given by the head of oil from the feeding reservoir and acts exactly as an open tank connected at the lower end of the section, at the same level as the feeding tank. In this first moment, therefore, half of the cable will be fed by the feeding tank and half by the pressure tank.

The curve calculated from formula (4) will apply also to the pressure tank and will have to be plotted from the point $B$, at the same level as the feeding point $F$, see Fig. 4, in opposite direction. But after a certain length of time, the pressure inside the tank and in the gas cells will be smaller on account of the volume of oil having been fed back to the line. The corresponding curve will have to be plotted not from a point at the same level as the feeding reservoir but from a point at the level lower than $B$ by a quantity $h_1$. This curve will cut the curve from $F$ at a point $D$ which divides the section $l$ in two parts, one fed from the feeding tank and one from the pressure tank.

The equation of the new curve will be

$$h = \frac{a\,b}{2\,\gamma}\,(l - x)^2 + h_1$$

The point $D$ where this curve cuts the curve

$$h = \frac{a\,b}{2\,\gamma}\,x^2$$

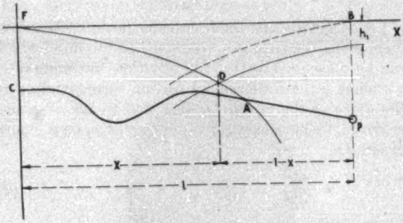

Fig. 4—Static Pressure Diagram with Feeding and Pressure Tanks

plotted from $F$, will be given by eliminating $h$ from these two equations, *i. e.*,

$$x = \frac{1}{2}\,l + \frac{h_1\,\gamma}{l\,a\,b}$$

The length of cable fed at that moment from $B$ will be

$$l - x = \frac{1}{2}\,l - \frac{h_1\,\gamma}{l\,a\,b}$$

If we consider a certain interval of time, $dt$, the length of cable fed by $B$ will absorb a volume of oil

$$a\,(l - x)\,dt$$

This volume of oil is given by the pressure tank and the volume of gas in its cells will accordingly increase by a quantity $d\,v$ equal to the amount of oil given out,

$$d\,v = a\,(l - x)\,dt$$

and substituting,

$$d\,v = a\left(\frac{1}{2}\,l - \frac{h_1\,\gamma}{l\,a\,b}\right)dt$$

Calling $p_1$ the hydrostatic pressure of the pressure tank at the beginning of the cooling period and $p$ the pressure at a certain moment, we will have

$$h_1\,\gamma = p_1 - p$$

and thus

$$d\,v = a\left\{\frac{1}{2}\,l - \frac{p_1 - p}{l\,a\,b}\right\}dt$$

From the characteristic equation of gases

$$p\,v = p_1\,v_1 = K$$

we have

$$d\,v = a\left\{\frac{1}{2}\,l - \frac{p_1 - \dfrac{K}{v}}{l\,a\,b}\right\}dt$$

Integrating this equation between the time zero, beginning of cooling period, and a time $T$, we have:

$$\int_{V_1}^{V} \frac{d\,v}{\dfrac{1}{2}\,l - \dfrac{p_1 - \dfrac{K}{v}}{l\,a\,b}} = \int_0^T a\,d$$

This supposes $a$ to be constant during this time which is a condition of greater safety.

The second integral is nothing else than the volume required by the unit of length of cable when cooling down from the temperature at the time zero to the temperature corresponding to the time $T$. Let us call it $Q$.

Solving the first integral, we obtain:

$$V_1 = \frac{A\,Q}{\dfrac{B}{A}\log_e \dfrac{B - A}{B - A\dfrac{V}{V_1}} - \dfrac{V}{V_1} + 1}$$

where

$$B = \frac{p_1}{l\,a\,b} \text{ and } A = B - \frac{1}{2}\,l$$

For $A = 0$, the above expression gives a result equal to zero and therefore is of no use. One of the ways to solve the problem is to suppose $A = 0$ before making the integration and then we have the result,

$$V_1 = \frac{2\,B\,Q}{\dfrac{V^2}{V_1^2} - 1}$$

which gives values practically exact also if $A$ is not zero but only small with respect to $B$.

This expression was used to calculate the volumes $V_1$ of the gas in pressure tanks when at the pressure $p_1$ and thus the volume of gas at atmospheric pressure to be contained in the cells.

Up to this point, only the drop of pressure which takes place in the cable when the load is dropped, has been considered.

The increase of pressure which is caused by the oil expansion under load can be studied very simply by changing the sign of coefficient $a$ in all the formulas written.

If the line is calculated in such a way that during cooling the pressure never drops below atmospheric, it is easy to see that during the heating period the pressure will increase to a value about double the hydrostatic head.

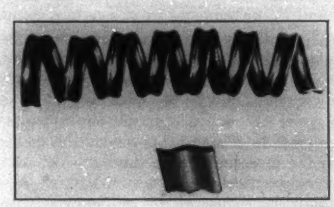

FIG. 5—COPPER SPIRAL FOR HOLLOW CORE CABLE

*Determination of Coefficient b.* As no data were readily available on the movement of viscous liquid inside a tube, a series of experiments was conducted on a lead tube immersed in a water bath at different temperatures, the flow of oil being supplied by a reservoir at a certain height over the tube; the drop of pressure along an established length and the times required by a certain quantity of oil to flow out were measured. It was found that within the limits of the viscosity of the oil to be used and for the flows to be expected in the cable, the drop of pressure could be considered proportional to the flow and the formula of Poiseuille was exact enough for the purpose.

Experiments were made also on the effect of a metal spiral inside the tube and after several tests it was recognized that in order to reduce, to a minimum, the resistance to the flow, it was advisable to use a supporting spiral of very small thickness. The spiral shown in Fig. 5, made up from a specially shaped copper tape so as to give the required mechanical strength, was adopted.

*Calculation of Coefficient a.* The variations of temperature in the cable due to load variations are of much greater importance than those due to variations in the temperature of the surrounding medium, and coefficient $a$ is calculated on this base.

Let us suppose that the cable is working at a certain load and that $W$ watts per unit of length are dissipated from its external sheath. When the load is removed, the temperature of the outside surface will remain for a certain length of time the same as under load and the same number $W$ of watts will be dissipated. These watts will be given out by a corresponding cooling down of the internal points of the cable. For a first approximation, we may calculate the value of $a$ per unit of length assuming that the watts dissipated by the load are equal to the sum of the various products of the specific heat of each elementary volume of cable by its corresponding drop of temperature.

The cable may be divided into three parts:

1. The copper conductor and the oil contained in the tube and between the wires. This part may be considered as all at the same temperature, on account of the high conductivity of the copper and the fluidity of the oil. Let us call $c_1$ its average specific heat, $v_1$ its volume, and $T_1$ the temperature at a certain moment.

2. The insulation where the temperature varies from point to point. Let us call $c_2$ the average specific heat of the paper and the included oil, $d\,v_2$, the elementary volume in a point, and $T_2$ its temperature at a certain moment.

3. The lead; in this first approximation let us consider only the interval of time during which the lead temperature practically does not change; we can then forget about it. This, of course, neglects the lead losses.

We may then write

$$W = C_1\,v_1 \int \frac{d\,T_1}{dt} + C_2 \int \frac{d\,T_2}{dt}\,d\,v_2 \qquad (6)$$

If we call $E_1$ the volume of oil absorbed by each unit of volume of the part 1 of the cable, for one degree temperature variation, and $E_2$ the corresponding volume for part 2, we can write that

$$E_1\,v_1 \int \frac{d\,T_1}{dt} \text{ and } E_2 \int \frac{d\,T_2}{dt}\,d\,v_2$$

represent the total volume of oil absorbed by the conductor and by the insulation, for every second, at that particular moment.

If we call the first expression $a_1$, and the second $a_2$, we may from (6) write

$$W = a_1\,\frac{C_1}{E_1} + a_2\,\frac{C_2}{E_2}$$

which is not sufficient to calculate $a_1 + a_2$.

We can consider, however, that in the very first moment after the load was removed, only the conductor will begin to cool down and that therefore

$$a = a_1 \text{ or } W = a\,\frac{C_1}{E_1}$$

It is then possible to calculate readily the initial value of $a$. It is interesting to note that this value is independent of the surrounding medium and depends only upon the number of watts which are dissipated.

After a short time the value of $a$ will be an average between the initial value corresponding to the copper conductor alone

$$\left(W = a\,\frac{C_1}{E_1}\right)$$

and that corresponding to the insulation,

$$\left(W = a\,\frac{C_2}{E_2}\right)$$

It is evident that when the lead starts to cool down, the watts dissipated will also diminish and thus also $a$ will accordingly decrease.

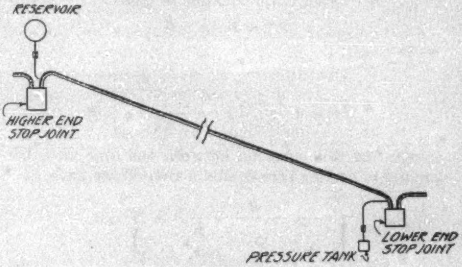

FIG. 6—SCHEMATIC DIAGRAM OF CABLE SECTION

For sake of safety in the design of the cable, the greater of the two values corresponding respectively to the conductor and to the insulation has been chosen. The lead losses have been included in $W$ and while their effect on coefficient $a$ is rather complicated they have thereby been amply provided for. On this basis it was possible to calculate the dimensions of the cable. As said above, it was found necessary to divide the total length of the line into various sections each separately fed by oil reservoirs. With the exception of a few sections where the length was determined by the maximum hydrostatic pressure of the oil in the cable on account of the steep grade of the profile, the length of the sections was calculated assuming a certain diameter of the central passage, taking the value of $a$ for the corresponding cable and of $b$ in the conditions of minimum winter temperature, maximum viscosity of the oil, and then plotting the length of the sections in the graphical way described above.

Keeping in view the conditions of the profile, the cost of the special joints to be installed between the sections and the cost of the cable as a function of its diameter, the best possible subdivision of both the New York and Chicago lines was obtained. It is evident that a difference in cost of the special joint between sections of the feeding reservoirs or of the installation methods may lead to a different subdivision of the same line.

Each standard section of the line consists essentially, as shown in Fig. 6, of two stop joints which close the central oil passage in such a way that the oil of one section has no connection with the oil of the next section, of one set of feeding tanks which gives oil to the cables, and, in certain special conditions, of a pressure tank which supplements the oil supply to the cable.

*Cable design.* The cable installed in New York and Chicago is shown in Fig. 7. The conductor is made up of two layers of copper wires each 103.5 mils, (2.6 mm.,) in diameter stranded over a spiral of hard-drawn copper tape, specially shaped, see Fig. 5, so as to reduce the friction of the oil, as previously explained. The clear diameter inside the spiral is 0.75 in., (19 mm.,) and inside the first layer of copper wires is 0.85 in., (21.5 mm.). To facilitate the passage of oil between the stranded wire, from the central passage to the insulation special stranding was used. The outside diameter of the copper is 1.22 in., (31 mm.) The insulation thickness is 23/32 in., (18.3 mm.,) made up of wood pulp paper in three different gradations, depending upon the porosity. A mineral oil a little more viscous than that used in transformers is used for impregnating the cable.

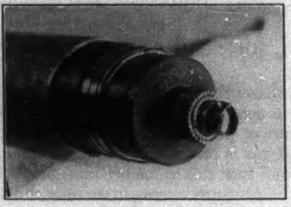

Fig. 7—Illustration of 132-Kv. Cable

After the impregnation at the factory and the electrical tests, the oil inside the central passage was removed before sealing the cable ends. The reason for this was to avoid the possibility of temperature variations during shipping, causing deformation of the lead sheath. The cable, as described later, was reimpregnated in the field after installation. Immediately after the high-voltage test and before removing the oil, an ionization test, difference between power factors at 20,000 and 95,000 volts, was made in the usual manner and also a special test, to determine the quantity of free gas inside the cable. This test, called an impregnation test, will be described later. After this test, a reinforcing armor made from a hard-drawn copper tape was wrapped over the first sheath lead between two layers of impregnated paper. Over this armor a second lead sheath was applied to protect the copper tape against the chemical action of the ground and to give a smooth surface while pulling into the ducts. It was necessary to use this reinforcement because the cable during operation is continuously subjected to the hydrostatic presure, as high as 105 ft. (32 m.) of oil, and this pressure may increase considerably when sudden loads are applied.

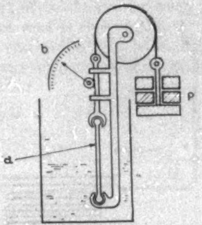

Fig. 8—Lead Testing Machine

A plain lead sheath would not have been able to withstand such pressure, even if its thickness was very great. Lead has more the characteristics of a liquid of extremely high viscosity than of a metal, and is deformed under the slightest stress. In this connection, the results of some tests made in Milan are quite interesting.

A sample of lead *a*, see Fig. 8, was subjected to a certain tension given by a weight *p* while immersed in an oil bath at constant temperatures, the index giving the elongation.

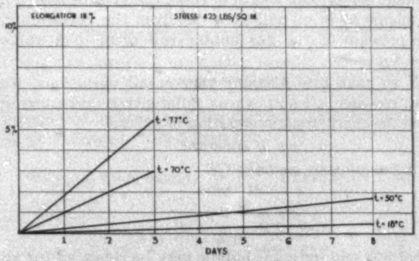

Fig. 9—Elongation Curves of Commercial Lead

Several tests at different temperatures and with different weights were made for different qualities of lead and for the alloys generally used in cables, (tin or antimony) showing that, as a rule, the lead keeps on elongating in a more or less regular way up to the breaking point, while for very small loads and low temperatures, the deformation stops after a short time.

The speed of deformation increases rapidly with the temperature as shown in Fig. 9 which gives some of the results obtained.

*Impregnation Test.* One end of the cable being sealed, see Fig. 10, the other end was connected through a valve *a* to an oil reservoir at a higher level than the cable; at this same end a mercury manometer was provided and a valve *b* through which a certain quantity of oil could be drained from the system. If the valve *a* is shut, the manometer still indicates the pressure corresponding to the head of oil of the reservoir over the mercury level, but if the lead tube is not elastically deformed by the pressure and no free gas is occluded in the cable, no oil should come out when opening the valve *b*. Not taking into account for a moment the elasticity of the lead tube, it is evident that if a bubble of gas of volume $v$ at a pressure $p$ exists in a point of the cable, it will expand when opening the valve *b*, and assume, in a certain length of time, the volume $v + \Delta v$. A volume $\Delta v$ of oil will come out from the valve *b* and the pressure of the gas bubble will drop to a value $p - \Delta p$.

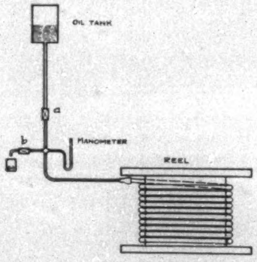

FIG. 10—METHOD OF MAKING IMPREGNATION TEST ON REELED CABLE

If we take into account very small variations, we may consider $\Delta v$ and $\Delta p$ as differentials and starting from the characteristic equation of gases,

$$p\,v = \text{constant}$$

by differentiating, we have

$$d\,v = -\,d\,p\,\frac{v}{p}$$

What was said for a gas bubble may be repeated for all the bubbles existing in the cable and

$$\Sigma\,d\,v = -\,\Sigma\,d\,p\,\frac{v}{p}$$

But the sum of all the $d\,v$ is the total amount of oil drained from the valve *b*; calling it $\Delta v$ and considering that $\Delta p$ is the same for every point of the cable and can be read on the manometer, we have

$$\Delta v = -\,\Delta p\,\Sigma\,\frac{v}{p}$$

If the pressure is the same for every point of the cable, the total volume of free gas in the cable can be calculated readily. This condition of equal pressure in every point can be realized practically at the factory by laying the reel on one of its flanges, as shown in Fig. 10, and using a pressure $p$ high enough. A very important and interesting point came out from the comparison of this mechanical test and the electrical test in the fact that the part of power factor corresponding to the ionization is proportional to the volume of gas in the cable as measured. In Fig. 11 the values of the variation of the power factor between 20,000 volts and 95,000 volts are plotted against the ratio of the quantity of free gas in the cable, to the total volume of the dielectric, the oil pressure being between the limits of atmospheric and atmospheric plus one meter head of oil.

In the impregnation test taken in the field, it is not possible to consider the pressure of the gas the same in the various points of the cable, with the exception of flat sections. Only the total amount $\Sigma\,\frac{v}{p}$ can be known. Apparently this expression does not seem to mean very much, but when we consider that on one hand the part of power factor due to the ionization of the occluded gas is proportional to its volume, and on the other hand that this value becomes proportionately smaller as the pressure increases, we may conclude that the expression

$$\Sigma\,\frac{v}{p}$$

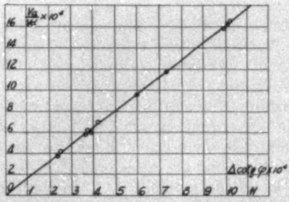

FIG. 11—RELATION-POWER FACTOR CHANGE TO ENTRAINED GAS

is a quantity which allows us to judge the electrical behavior of the cable. For this reason we have considered it as a measure of the impregnation of the cable.

It should be here noted that in the actual determination of $\Sigma\,\frac{v}{p}$ by test finite increments of pressure and volume are considered and these must accordingly be kept small in order to avoid an appreciable error in the results.

When we started using this method in the field we met with the trouble that the oil pressure in the cable was not constant but changing from time to time due either to the variation of the temperature of the cable, or when the test was taken a few hours after impregnation, to the fact that the impregnation was not yet completed, especially in the joints. A method was made possible under these conditions in the following way: Let us suppose the pressure in a gas bubble of volume $v$ be $p$, and $p$ be a function of the time, $t$. At a certain moment we open a valve and let a certain volume of oil $d\,v$ flow out. The pressure which at that moment was $p_1$ drops down to $p_1 - d\,p_1$ and then continues to change according to a law similar to that of before. Let us suppose we know the mathematical connection between $p$ and $t$

$$p = f\,(t\,a, b, c, \ldots.)$$

This includes certain constants $a, b, c, \ldots.$ depending upon the conditions of the cable. It is always possible to alter the same equation in such a way as to put in evidence beside or instead of some of the constants the value of $p$ and $v$ at a certain time $t_1$ say $p_1\,v_1$. The equation becomes

$$p = f\,(t_1\,p_1\,v_1 \ldots.)$$

It is now possible to take the differential of $p$ in respect to $p_1$

$$d\,p = d\,p_1 \frac{d\,f\,(t_1\,p_1\,v_1 \ldots.)}{d\,p_1}$$

As we have to deal with gaseous bubbles, we can write

$$d\,p_1 = -\,d\,v_1 \frac{p_1}{v_1}$$

and then

$$\frac{v_1}{p_1}\,d\,p = -\,d\,v_1 \frac{d\,f\,(t_1\,p_1\,v_1 \ldots.)}{d\,p_1}$$

This gives the variation of $p$ at any time in consequence of the variation $d\,v_1$ introduced at the time $t_1$.

If we write the same equation for all the bubbles in the cable and sum them, we obtain

$$d\,p \sum \frac{v_1}{p_1} = -\,\frac{d\,f\,(t_1\,p_1\,v_1 \ldots.)}{d\,p_1} \sum d\,v_1$$

which permits us to know at any time the variation of $p$ due to the variation of $\Sigma\,v_1$ to $\Sigma\,v_1 + \Sigma\,d\,v_1$.

$\Sigma\,d\,v_1$ is the total amount of increase of volume of the gas bubbles at the time $t_1$ and can be produced by the subtraction from the cable of the same amount of oil. Let us call it $\Delta\,v_1$

At the time $t_1$ we have

$$\frac{d\,f\,(t,\,v_1,\,p_1 \ldots.)}{d\,p_1} = 1$$

$$\Delta\,v_1 = -\,\Delta\,p_1 \sum \frac{v_1}{p_1}$$

The method is then as follows:

At the end of the cable, see Fig. 12, where the feeding tank is installed, a mercury manometer is connected. When the valve $a$ is closed, it starts indicating the pressure in the cable. Let us take records of this pressure and plot the curve 1. At the time $t$, we open the valve $b$ and let some oil out. We then close the valve and continue to read the pressure indicated by the manometer. The curve which would have been followed if no oil had been taken out is shown dotted. The true curve is shown a little lower and marked *2*.

The first part of this curve between the times $t_1$ and $t_2$ is a transient and is due to the settling of the new conditions in the cable. It is not possible then to know $d\,p_1$ in any other way than prolonging the part considered as steady of the curve 2 to cut the ordinate $p_1$ as is shown by the dotted line.

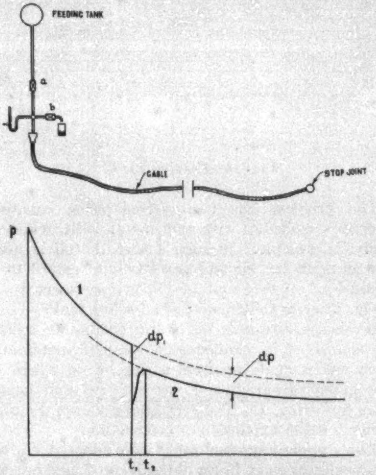

Fig. 12—Method of Making Impregnation Test on Installed Cable

We have then, easily, $\sum \frac{v_1}{p_1}$ from the formula.

$$\Delta\,v_1 = -\,\Delta\,p_1 \sum \frac{v_1}{p_1}$$

Of course, $\sum \frac{v_1}{p_1}$ corresponds to the pressure $p_1$ at the end of the cable and not to the pressure given by the feeding tank but in practise this difference can be kept very small.

A correction was introduced to take care of the extension of the joints of the lead tube and of the pipes included in the system.

*Description of the Special Accessories: Feeding Tanks.* The principal requisites of the oil tanks are that the oil inside should always be practically at atmospheric pressure, independently of the volume of oil present in the tank, and that it should be in no way in contact with the surrounding air.

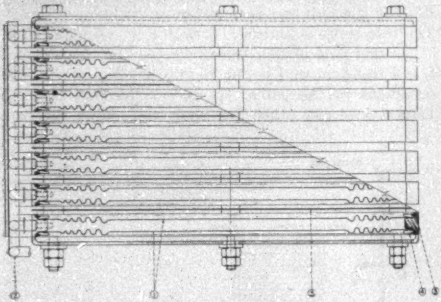

Fig. 13—Feeding Tank

The problem has been solved using collapsible reservoirs made up with thin metal walls, which are easily deformable. In such a way the oil is not in contact with the air and yet acts with regard to the pressure as if it were contained in an open reservoir.

Fig. 13 gives the drawing of a feeding tank.

Seven separate cells, each with collapsible walls, *1*, are connected in parallel to a common manifold, *2*. Each cell is made up from a ring, *3*, on which two corrugated diaphragms, *1*, are soldered and kept in place by a ring, *4*. The corrugation allows the plates to move under expansion or contraction.

Two standard types of tanks were adopted, one with seven cells, as given in Fig. 13, called *S*-7, and one with 11 cells called *S*-11.

Each cable of a section was fed by two or more of these tanks, paralleled by means of valves and manifolds. Fig. 14 gives the value of the pressure of the oil inside *one* cell of a feeding tank, against the volume of oil in it, the pressure being given in centimeters of head of oil referred to the center of the tank, and the volumes in liters.

The area included in the curve is due to the hysteresis of the metal walls when deformed. See Fig. 14.

*Pressure Tanks.* As said before, the characteristic of this type of tank, Fig. 15, is to have a certain number of collapsible air-tight cells, *3*, full of gas, separated by heavy plates, *5*, contained in the tank, *2*, which is filled up with oil. The outside tank, *1*, is able to withstand the maximum pressures given by the oil of the section during expansion.

Each cell is perfectly tight and is filled with an inert gas, *6*, especially selected for the purpose.

Three standard types were adopted: *A*23 with 23 cells, as shown in Fig. 15, *A*17 with 17 cells, and *A*6 with 6. The curve of Fig. 16 shows how the pressure inside the tank varies as a function of the volume of oil given out by the tank, for a pressure tank of the type *A*6, pressures being expressed in $Kg/\text{cm}^2$. above atmospheric, volumes in liters.

*Stop-Joints.* As has been explained in the design of the cable, each section is connected electrically to the next one by means of a special joint, called stop-joint, which cuts the oil communication between them. See Fig. 17. The stop-joint consists essentially of a cylindrical tank, *1*, full of oil, *2*, which contains two inserted porcelain terminals, *3*, in a *V* arrangement.

The end cables of each section terminate in these potheads which are electrically connected at the lower part. As for the pressure tanks, the outer tank is of suitable thickness and has a lining, *5*, hermetically sealed to the upper cover, *6*. The terminal's insulators are cemented at the upper end to the cover and are provided at the lower part with two cemented metal caps, *7*; the tightness of the seams is guaranteed by composition cork gaskets.

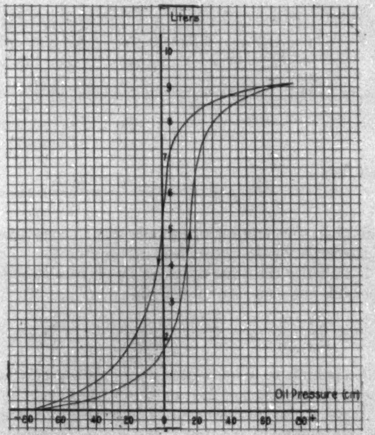

Fig. 14—Pressure-Volume Relation of Feeding Tanks

The two caps are electrically connected by a flexible connection, *4*, and carry in the inside a set of brushes, *8*, for the contact with the connector, *9*, which is soldered at the end of the cables. The two lower caps and the connection, *4*, are screened by a metal box, *11*, so as to have a good distribution of the electric field; for the same reason the insulators are provided at the upper end with electrostatic controls, *12*. The metal screen, *11*, is reinforced electrically with paper wrappings, *18*, and the discharge path to the case is protected by insulating barriers, *19*. The two end cables after being reinforced in the field with paper wrappings, *10*, and provided with electrostatic controls, *13*, are slipped inside the insulators so that their connector, *9*, is wedged between the brushes, *8*, and the lead sheath of the cable is soldered to the cover, by means of metal sleeves, *14*. As a matter of fact, the stop-joint tank is *raised* from a pit in the manhole up to its final position so that the cables slip inside the insulators. The only wipes to be made in the field are those at *15*. The oil is fed to the cables through a pipe, *16*, which is connected to the reservoirs at the feeding end of the section.

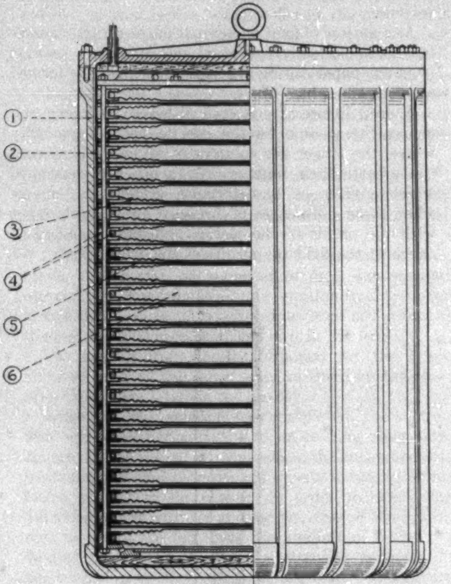

Fig. 15—Pressure Tank

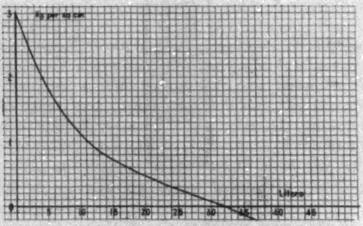

Fig. 16—Pressure-Volume Relation of Pressure Tanks

The oil chamber, *2*, inside the stop-joint is connected in the field through the pipe, *17*, to the terminal at the higher pressure, each terminal being at the pressure given by the height of the reservoir of the section to which it is connected. In this way, the oil in the tank is always at the same or at a higher pressure than the oil inside each of the insulators and the porcelain is subjected only to compression.

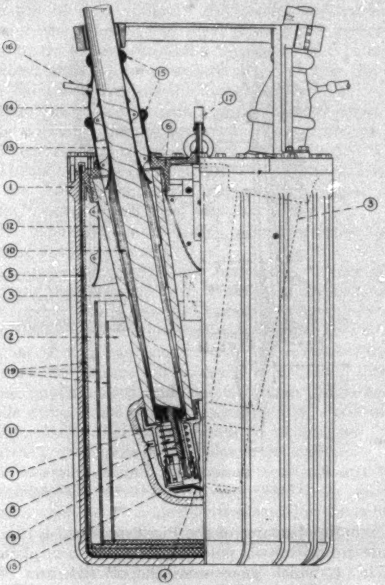

Fig. 17—Stop-Joint

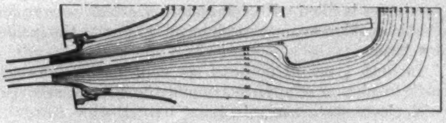

Fig. 18—Electrostatic Stress in Stop Joint

The distribution of the electrostatic field inside the stop-joint has been studied in the laboratory in an experimental way, plotting point by point the equipotential lines of a special model with the well-known electrolytic method, and is given in Fig. 18. The equipotential lines are taken on a section passing through the insulator's axis.

*Terminals.* Fig. 19 gives the drawing of a Pirelli pothead. This is essentially the same as the type developed by the General Electric Co. for this purpose, shown in Fig. 20. The upper connection, *1*, is provided with suitable openings, *2*, for the oil passage and the bottom connections, *3*, are provided for the oil pipes to the reservoirs. One of the outstanding features of the Pirelli terminal is that it is made up with two porcelain insulators, a plain one inside, *4*, which guarantees the oil tightness of the system, and one outside, *5*, made up of several elements with petticoats which provide a long longitudinal path for surface leakage. The space between the two insulators is filled with compound, *6*, which acts as an elastic cushion against mechanical strains to the inside insulator.

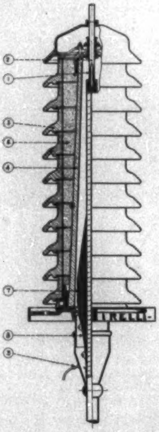

FIG. 19—PIRELLI TERMINAL

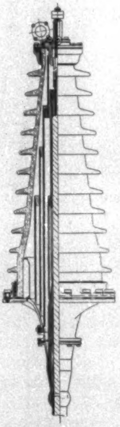

FIG. 20—GENERAL ELECTRIC TERMINAL

In both types of pothead the cables are reinforced with insulation wrappings, *7*, and the stresses relieved with electrostatic controls, *8*.

*Impregnation of the Cable in the Field.* The installation and the following impregnation of the cable in the field were most delicate operations. This second impregnation was considered necessary so as not to trap air at the jointing points, and also, if the cable had been shipped and installed with the core full of oil, some of it would certainly have drained out during the splicing, especially due to the fact that the majority of the lengths were not laid level.

The operation was carried on in the following way: All the lengths of a section were spliced together and the end stop-joints, or terminals, of the section were installed. A certain number of joints along the section were not made up in the final way, but were built in a provisional way, as shown in Fig. 21, so as to permit the evacuation of the cable, not only from the true ends, at the stop-joints, but also at intermediate points of the section.

As a matter of fact, on account of the central passage not being perfectly free of oil, due largely to seepage from the paper during evacuation, oil slugs are formed all along the cable.

A drop in pressure is created across each slug and causes the vacuum in the core to become gradually worse, the longer the columns of oil in the slugs and the greater their number. A theory was developed which enables us to determine, graphically, exactly what these differences of pressure are in accordance with the profile of the section and also a method to check in the field the results of the calculations. We can in this way calculate the distances between the provisional joints so that vacuum not poorer than a predetermined value will be developed, and this can be checked in the field.

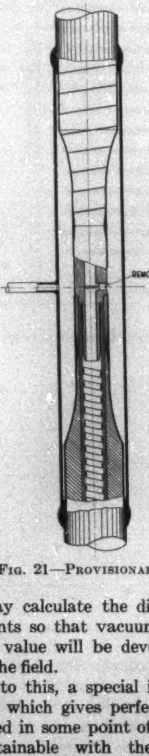

FIG. 21—PROVISIONAL JOINT

In addition to this, a special impregnating process was developed which gives perfect results even if the vacuum reached in some point of the cable is not the maximum obtainable with the pumps. This reimpregnation in the field involves only a small portion of the cable, probably only the central hollow passage and an adjacent thin layer of the insulation. Under such conditions, the gas occlusions which may remain in the core during this second evacuation are only a small percentage of this volume and therefore a minimum portion of the total volume of the cable. The vacuum, as said before, was applied at the stop-joints and at the provisional joints. After a certain number of hours, the impregnation was started by admitting oil into the core at the point where the feeding tanks are connected. The vacuum pumps at each provisional joint manhole were stopped after the oil had arrived at this location on all three conductors and had been carefully tested.

The impregnation of the cable was practically ended with the arrival of the oil at the stop-joint at the far end of the section and after the insulation and the joint had ceased absorbing oil.

After this an impregnation test as described was made; such a test, as a matter of fact, was studied especially to determine the impregnation quality, after installation, as it is not possible or at least not practical to take electrical measurements of it in the field.

The impregnation results obtained on the cable installed were of the same order as those on the reels after the impregnation in the factory.

When the impregnation was completed, the section was connected permanently to its feeding reservoirs. Before putting the cable in operation, the entire line was heated to full-load temperature several times by circulating current in the copper, in order to check the behavior of the various accessories, the oil flows, and also to verify the fact that the amount of oil in the feeding tanks was exactly the quantity required in accordance with the load and seasonal temperature variations.

This heating process was also used in some special instances to decrease the viscosity of oil and accelerate its flow during impregnation, when the weather was rather cold.

Incidentally, one of the advantages of this type of cable is that if any leak exists in the joint wipes or other connections, it will be immediately detected during evacuation, or if of later development, by the application of the oil pressure. In the usual type of cable, similar leaks, especially in those parts of the line which are completely under water, would allow the entrance of moisture, resulting sooner or later in the failure of the cable without preliminary indication.

## Manufacture, Inspection, and Testing of the 132,000-Volt Cable

By Wallace S. Clark[3]
Associate, A. I. E. E.

There are certain novel features in the manufacture of the cable which are, we hope, of sufficient general interest to warrant their introduction here.

In order to secure a central passageway through the conductor, a spiral of hard-drawn copper strip was formed and the wires composing the conductor proper were stranded around this. Special machinery was installed to make this spiral and special precautions had to be taken in stranding the individual wires around it, the inner layer of wires being dented to give free circulation of oil.

The wood pulp paper used in forming the insulation wall was of three different thicknesses and varied in density, the thinnest and most dense paper being put next to the conductor where the electrical strains are greatest, then the intermediate paper, and on the outside the least dense and thickest paper.

After the core was completed, a radical departure from ordinary practise occurred. The insulated core had the first lead sheath applied, was wound on a reel and heated by immersing it in a steam bath. The ends of the cable were sealed and insulated leads were brought out through these seals.

The exhaustion of the heated cable core with vacuum pumps was the next step.

Measurements were taken periodically of the power factor of the cable and the insulation resistance between the conductor and the lead sheath during the evacuation. The particularly interesting point in this process is that if the lead sheath has any imperfections in it, moisture (steam) will naturally be sucked in through these imperfections and the electrical measurements made will indicate that this is happening. This makes it improbable that there should be undetected faults, such as porous spots or pin-holes in the lead.

When the desired electrical measurements were obtained, oil, which previously had been given a special treatment for purification and for the removal of all absorbed gases (ordinary transformer oil will absorb from 15 to 20 per cent of its own volume of air), was admitted to the central core very slowly, saturating the paper wall.

The cable was finally cooled down under oil pressure and when room temperature was reached, it was taken from the tank and was ready to test.

After testing, the ends were hermetically sealed and the cable was then ready to receive its armor and outer jacket of lead.

The armoring consisted of wrapping the inner lead sheath with treated paper tape; next with a thin hard-drawn copper tape; then a second paper tape. The cable was then taken back to the lead press and leaded over all, and was made ready for shipment on especially large bodied reels, after removal of the oil.

*Tests.* The specified tests were similar to those of the A. E. I. C. Specifications, and the principal ones were as follows:

a. Each reel of cable had to stand 175,000-volt alternating current for 15 min. between conductor and sheath.

b. Samples maintained at 0 deg. cent., freezing, for two hours were bent three cycles to 180 deg. around a drum having a diameter 15 times the diameter of the cable, and then withstood 225,000-volt alternating current for five minutes.

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[3] General Electric Company.

c. One full reel of cable from each 15,000-ft. lot was tested with 140,000-volt alternating current for eight hours.

d. The original specifications called for a test after installation of 140,000-volt alternating current for 15 min. between conductor and sheath. As it was impractical to secure transformers for this, special kenotron testing sets were provided in New York and Chicago, and the cable successfully tested with 300,000-volt direct current for 15 min.

The maximum power factor on any one section of cable at room temperature did not exceed ½ of 1 per cent, and the power factor at 65 deg. cent., maximum operating temperature, did not exceed 0.65 per cent. The difference in power factors, ionization, when measured at stresses of 20,000 and 95,000 volts, 28 and 132 volts per mil, respectively, did not exceed 0.2 per cent. The average figures were very much better than these.

In connection with the ultimate breakdown tests, which were performed on these samples after they had passed all the required voltage tests, it is interesting to note that comparing the breakdown tests with those made on General Electric cables of standard type without oil ducts and intended for maximum working pressure of 75,000 volts, and having only 1/64-in. thicker insulation, the short time breakdown voltages were about the same; but with long time tests at lower voltages, the oil-filled cable far out-distanced the ordinary type.

*Special Tests.* Samples of cable were run 24 hr. at 225,000-volt alternating current without breakdown or injury. This was three times the working stress.

The five-min. breakdown on samples was about 400,000 and the one-hr. breakdown about 300,000-volt alternating current.

One special test at Milan ran 30 hr. at 200,000-volt, after which the potential was raised to 260,000-volt alternating current and held for 20 hr. without failure.

A very interesting feature shown by the special tests was that a length of cable could be tested and the constants determined; then, after a heating and cooling cycle, be remeasured substantially without change in the results. This is one of the best guarantees of minimum electrical deterioration which can be determined by test.

The general results at Milan and Schenectady showed good agreement, even though some of the Milan tests were made at 42 cycles instead of 60 cycles, and all tests exceeded the specifications by a large margin.

Duplication of manufacturing processes at Schenectady and Milan was secured through the freely offered assistance of the Pirelli engineers and the constant interchange of manufacturing data.

*Inspection.* All cable manufactured for the New York Edison and United Companies, both at Milan and Schenectady, was inspected as to processes and all tests witnessed by the Electrical Testing Laboratories, which maintained a resident inspector at the Pirelli factory in Milan for about nine months, especially for this purpose. Cable for the Commonwealth Edison Company, manufactured at Schenectady, was also inspected by the Electrical Testing Laboratories while that manufactured at Milan was inspected by Messrs. Guido & Marco Semenza, representatives of Merz & McLellan, Consulting Engineers, of London.

## Installation of the 132,000-Volt Cable

By A. H. Kehoe[4], Fellow, A. I. E. E.; C. H. Shaw[5], Associate, A. I. E. E.; J. B. Noe[5], Associate, A. I. E. E.; and D. W. Roper[6], Fellow, A. I. E. E.

*Location and Description of Route.* In New York the cable runs from the Hell Gate Generating Station of The Edison-United Companies, northward through the Borough of Bronx and up to the Dunwoodie Distributing Station, in the city of Yonkers, Westchester County, a total distance of about 12 mi. The feeder will be used to supply the rapidly growing area of Westchester County, immediately north of New York City, having in mind also the possibility of its use in the future as a link in the supply of water power from the St. Lawrence district directly into the metropolitan area of New York.

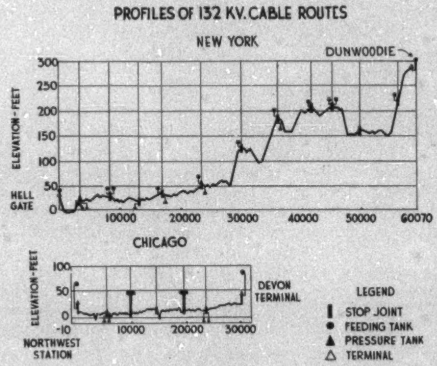

Fig. 22—Profiles of 132-Kv. Cable Route

In Chicago, the 132,000-volt feeder runs from the Northwest Generating Station of the Commonwealth Edison Company northward to the city line, a distance of about six mi., where it is connected to 30 mi. of overhead line, continuing northward to the Waukegan Station of the Public Service Company of Northern

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[4] United Electric Light & Power Company.

[5] The New York Edison Company.

[6] Commonwealth Edison Company.

Illinois. The line thus serves as a tie between generating stations, and transmits power in either direction, as may be required. As may be seen from the line profiles in Fig. 22, there is a difference in level of 285 ft. between the high and low points in New York, compared with 27 ft. in Chicago, excluding the river crossing. This difference in topography and grades made necessary radical differences in sectionalizing the line and the location and operation of the tanks supplying oil to the cable.

Figs. 23A and 23B show diagrammatically the connections of the New York and of the Chicago lines. Fig. 24 shows the initial transformer installation of 30,000-kv-a. capacity at Hell Gate. The initial installation at Chicago was 45,000 kv-a. In each location, provision is made for additional units to bring the transformer capacity up to the full line capacity of 90,000 kv-a.

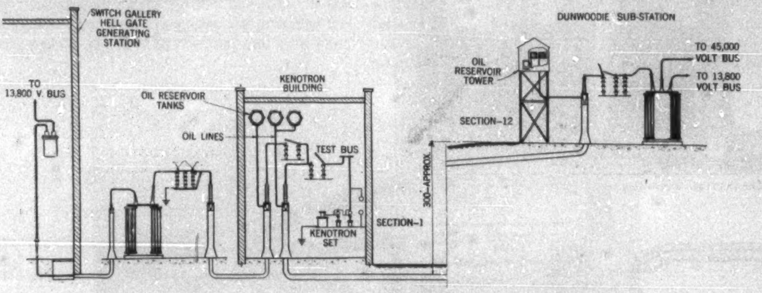
SWITCH GALLERY HELL GATE GENERATING STATION
TO 13,800 V. BUS
OIL RESERVOIR TANKS
KENOTRON BUILDING
OIL LINES
TEST BUS
KENOTRON SET
SECTION—1
300—APPROX.
DUNWOODIE SUB-STATION
OIL RESERVOIR TOWER
SECTION—12
TO 45,000 VOLT BUS
TO 13,800 VOLT BUS

Fig. 23A—Diagrammatical Connections of Line—New York

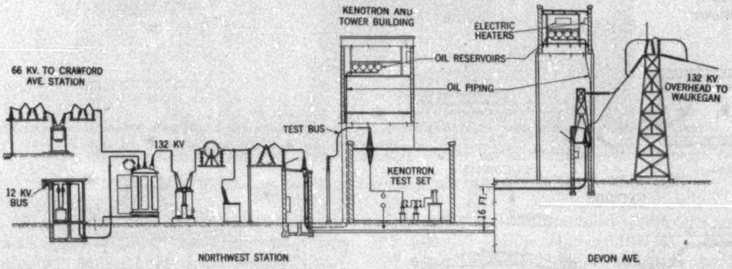
KENOTRON AND TOWER BUILDING
ELECTRIC HEATERS
OIL RESERVOIRS
OIL PIPING
66 KV. TO CRAWFORD AVE. STATION
132 KV. OVERHEAD TO WAUKEGAN
TEST BUS
132 KV
KENOTRON TEST SET
12 KV. BUS
16 FT.
NORTHWEST STATION
DEVON AVE.

Fig. 23B—Diagrammatical Connections of Line—Chicago

In New York, the southerly half of the feeder cable was Pirelli make, the northerly half, General Electric. In Chicago, the cable for two phases was supplied by the General Electric Company, and that for the third, by Pirelli.

*Conduit and Manhole Construction.* In 1925, preliminary surveys were made in both New York and in Chicago to decide upon the best routes for the 132,000-volt lines. Profiles were prepared and the routes were finally decided upon after consultation between the engineers of the two operating companies and those of the Pirelli and General Electric Companies. In both cities, entirely new conduit lines were constructed for the high voltage feeder, with duct space provided for the installation of a second feeder.

*Conduit Construction in New York.* In New York the conduit is of monolithic concrete construction, using 4-in. ducts, with two inches of concrete separation. In the Yonkers portion there are nine ducts, arranged three by three, and in the Bronx portion 12 ducts, built in the form of an inverted "T". The maximum cable length is 400 ft. for straight sections, curved sections being shorter in proportion to their curvature. Fig. 25 shows plan and elevation of the standard manholes used in New York and in Chicago and the method of racking the cable. Note especially the racking in the Yonkers manholes, which keeps the cables in a horizontal plane, each with an offset consisting of two full 90-deg. bends with a minimum bending radius of 24 in., allowing easy expansion and contraction of the cable with a minimum strain on the splice.

L-shaped angle manholes are placed where the direction of the system changes. Fig. 26 shows a typical angle manhole as used in New York.

The special stop-joint manhole, Fig. 27, of which there are 11 on the entire line, is 8 ft. wide, 12 ft. long, and 10 ft. deep, with a pit 4 ft. deep to allow for installing or replacing the stop joints. I-beams are built into the ceilings of these holes for lowering or raising the stop-joints. Normally the stop-joint tank rests on iron gratings placed over this pit, but these gratings can be removed when the joint is to be lowered.

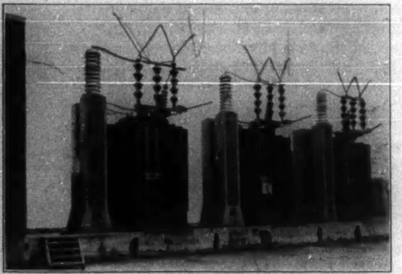

FIG. 24—INITIAL TRANSFORMER INSTALLATION AT HELL GATE

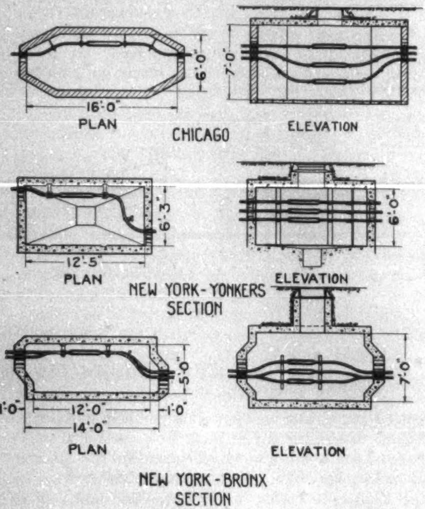
6'-0"
16'-0"
PLAN
CHICAGO
7'-0"
ELEVATION
6'-3"
12'-5"
PLAN
6'-0"
ELEVATION
NEW YORK-YONKERS SECTION
5'-0"
1'-0"
12'-0"
1'-0"
14'-0"
PLAN
7'-0"
ELEVATION
NEW YORK-BRONX SECTION

FIG. 25—STANDARD MANHOLES—NEW YORK & CHICAGO

In connection with the stop-joint manholes, reservoir manholes, Fig. 28, were constructed for the installation of the reservoir feeding tanks. These were located at a sufficient elevation from the stop-joint manhole to give the proper head of oil for feeding into the cable sections. I-beams were built into the ceilings of these holes for supporting the tanks. At three locations it was necessary to build special structures for containing the reservoir tanks, namely, at the Hell Gate Station, where the tanks are contained in a portion of the Kenetron Building, at the Yonkers city line, where a small house of a bungalow type was built, and at Dunwoodie Station where a tower was constructed.

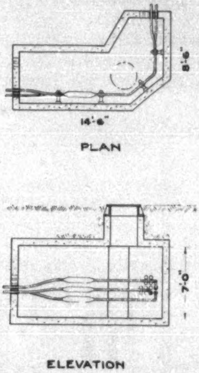
8'-6"
14'-6"
PLAN
7'-0"
ELEVATION

FIG. 26—TYPICAL ANGLE MANHOLES—NEW YORK

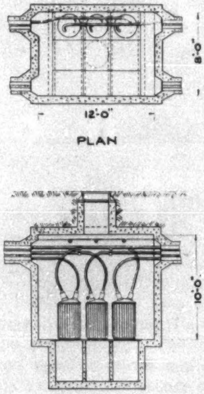
8'-0"
12'-0"
PLAN
10'-0"
ELEVATION

FIG. 27—TYPICAL MANHOLE FOR STOP JOINT

*Conduit Construction in Chicago.* The internal diameter of the ducts was four in. and the conduit structure consisted of eight ordinary precast concrete ducts, such as have been used previously in Chicago, laid in a two wide by four high formation. In order to avoid having any high points in the cable, the ducts were installed in a straight line between manholes wherever possible; otherwise the conduit was installed in one long radius bend, concave upward. The maximum distance between manholes was made about 500 ft. in order to prevent excessive strain on the cable during installation.

The manholes for permanent joints are 50 to 100 per cent larger than manholes used in the past, and were designed to accommodate a joint 5 ft. long and to permit training of the cable at radii of 30 in. or more.

The manholes for the stop-joints are 18 ft. long by 8 ft. wide by about 10 ft. deep and have a 4-ft. pit to facilitate the placing of the ends of the cable in the stop-joint tanks. Separate manholes are provided for the pressure tanks adjacent to the two end stop-joint holes.

*Towers.* In order that sufficient hydrostatic pressure might be maintained on the oil inside the cable, it was necessary that the feeding reservoirs be elevated above the section of the line being fed. In Chicago, where the ground contour was practically flat, this result was secured by placing the oil reservoirs in towers located at the ends of the line and at two intermediate points. In New York, it was possible by taking advantage of the hills to obtain sufficient pressure with the reservoirs located in manholes, except at the two terminals of the line. Figs. 29A, B, and C.

*Cable Installation.* On account of the radical differences between this cable and the types previously installed, and the fact that these were the first commercial installations of this new type of cable, many new problems were encountered during installation. In addition to the ordinary supervision by the forces of the operating companies, therefore, the entire work of installation was done under the direct supervision of the engineers of the manufacturers.

Due to the high voltage at which the cable is to be operated and to the hollow type of construction, extreme care was taken to ascertain that the ducts were of the proper size, entirely clean and free from obstructions before the cable was pulled. Special mandrels and brushes were pulled through each duct for this purpose, the cleaning being repeated, if necessary, until no more material was brought out. An elaborate series of pulling tests was made, using a continuous reading dynamometer rig, especially designed to determine the pulling tension. In these tests, grease and soapstone applied in various ways were thoroughly tested and their relative efficacy obtained, typical curves being shown in Fig. 30. The result was the adoption in both New York and Chicago of pulverized soapstone as a lubricant applied to the duct by the use of a series of flexible disks secured to a chain. The soapstone was inserted between the disks and deposited on the duct surface as the disks were drawn through the duct. As further precaution, some soapstone was added on the cable as it entered the duct.

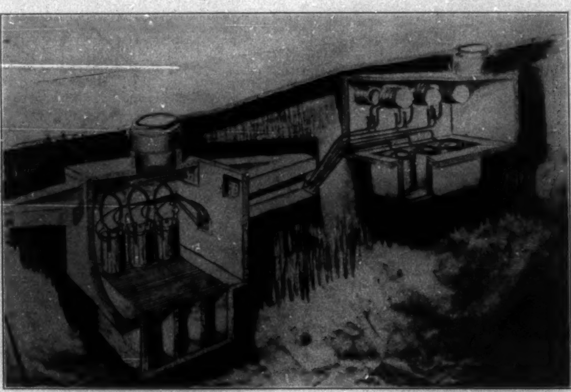
Fig. 28—Diagram of Reservoir Manhole Connections

In Chicago, about one-half of the cable route lay across open marshy country where the streets had not yet been cut through. This introduced serious problems in the transportation of the heavy reels and voluminous auxiliary apparatus, as well as the actual pulling of the cable, all of which difficulties were successfully overcome by the use of caterpillar tractors, trailers, and mud sleds; see Fig. 31.

Specially designed pulling eyes were installed on the cable by the manufacturers so as to prevent collapse of the central core during pulling and to keep the cable end completely sealed, Fig. 32.

In New York, during the pulling of the cable, thermocouples were wiped on to the lead sheath and pulled into the duct with the cable at six selected locations.

Complete records were kept of the pulling tensions obtained on every section, some average figures being:

| | |
|---|---|
| Straight 400-ft. section, down hill | 2400 lb. |
| Straight 400-ft. section, level | 3500 lb. |
| Curved 300-ft. section, radius 500 ft. | 4000 lb. |
| Average pulling tension | 9 lb. per ft. |

*Cable Splices.* While the manufacture of the cable at Milan and at Schenectady was practically identical, the standard joints were radically different, each manufacturer supplying the jointing material to be used in splicing his own cable.

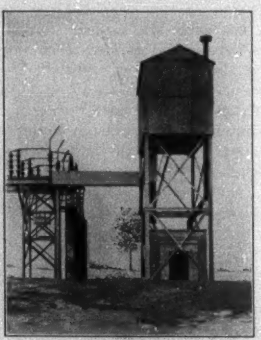

Fig. 29A—Dunwoodie Terminal Tower

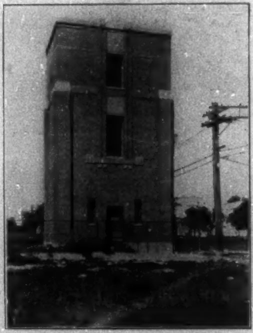

Fig. 29B—Bryn Maur Intermediate Tower—Chicago

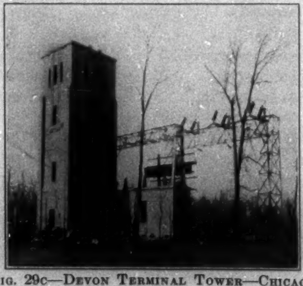

Fig. 29C—Devon Terminal Tower—Chicago

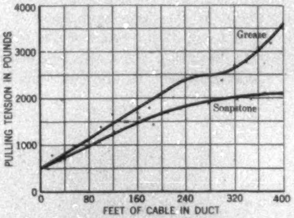

Fig. 30—Curves of Relative Pulling Tension—Grease and Soapstone

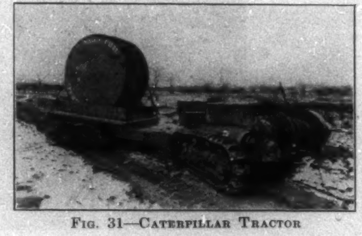

Fig. 31—Caterpillar Tractor

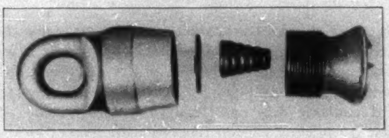

Fig. 32—Pirelli Pulling Eye

*Pirelli Type.* Fig. 33 illustrates the various stages in making, and the general design of the Pirelli joint.

The connectors for connecting the hollow core cable and continuing the passageway for oil in the center of the cable through the joint are similar in the Pirelli and General Electric joints. The connectors have in the center a transverse hole closed by a screw so that any joint, before it is insulated, can be arranged to communicate directly with the oil passage in the center of the cable.

The chief characteristic of the Pirelli joint is that the insulating material in the joint is paper which has been previously dried and prepared in the factory. This paper is not impregnated, but is surface-treated to reduce the absorption of moisture which might be collected during the process of jointing.

Another distinct feature is that the original insulation of the cable, after it has been properly penciled, is covered with a thin oil silk tape to reduce seepage of oil between the joint insulation applied in the manhole and the original insulation in the cable proper, the object being to evacuate and impregnate the insulation of the completed joint independently of the cable insulation.

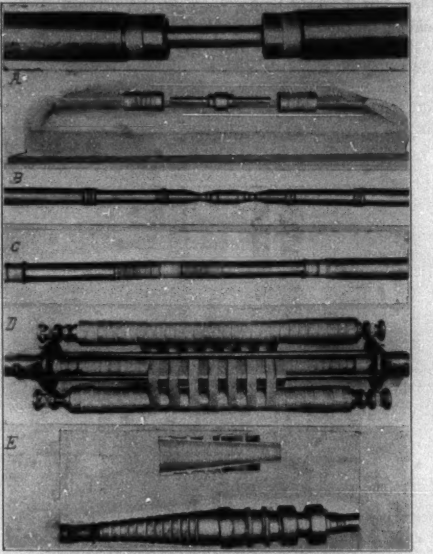

Fig. 33—Pirelli Joint Construction

Fig. 33c shows the insulation brought up to the original diameter of the cable insulation.

Fig. 33d shows the machine application of the specially treated paper reinforcing the insulation already applied.

Fig. 33e shows the aluminum shields which are applied to the finished insulated joint before the lead sleeve is put on. These shields act as controls of electrical stresses and allow free access of the oil to the joint insulation and at the same time, support the lead sleeve against collapsing during vacuum treatment.

The outside sleeve is of lead, usually split longitudinally for convenience in applying over the aluminum forms shown in Fig. 33e. After this sleeve is wipe-jointed to the cable and the seam soldered, it is reinforced with exterior armor so that it may compare in strength with the armored cable sheath. The length of the joint is 44 in., (1120 mm.) and the diameter inside is 6.2 in., (156 mm).

The completed joints, as described elsewhere, are field impregnated. Prior to adoption, these joints were thoroughly tested out at Milan.

*General Electric Type.* Fig. 34 illustrates the General Electric type of joint which, it will be seen, differs radically from the Pirelli joint: First, in having the original cable insulation stepped as shown in Figs. 34b and 34c to secure longitudinal dielectric strength, and second, in being taped by hand with specially prepared varnished cambric which is packed under oil in sealed containers and which is flushed with a special compound during taping. This insulation permits slow percolation of oil.

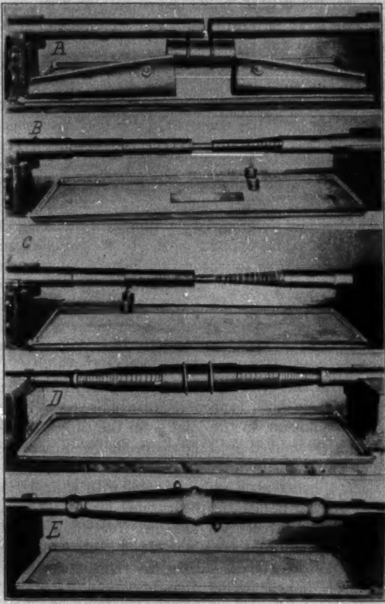

Fig. 34—General Electric Joint Construction

The joint is held concentric within the copper casing by the insulation cylinder and treated wooden wedges shown in Fig. 34.

The tapered ends of the insulation are wrapped with flexible copper tape which is united to the lead sheath of the cable, distributing the stresses at the ends of the joint and preventing any stress coming on thin films of oil between the insulation wrapped on the cable and the outer casing.

The two parts of the copper casing which telescope are united to the cable and to each other by wiped joints. In cases where corrosion is feared, the exterior of the copper casing is tinned all over.

The casings are stiff enough to resist any tendency to collapse during the evacuation of the cable in the field and are stronger against bursting pressure than the lead sheath of the cable. No interior or exterior reinforcements, therefore, are required.

The principles of the insulation and stress distribution of the joint are the same as those of the General Electric 45,000- and 66,000-volt joints which have had thorough field trials in several installations.

Short and long time over-voltage tests on the General Electric 132,000-volt joint have shown it to exceed in strength the original cable insulation. The length of the joint is 42 in. (1073 mm.) and the diameter inside is six in. (153 mm.)

Before any joints were constructed in the field, the splicers, foremen, and engineers were given a very careful training in the details of construction at the shops of the operating company, under the direct supervision of the manufacturers' engineers. The New York company sent a special delegation of foremen and splicers to Pittsfield, where they were given instruction in the making of the General Electric joint.

The splicers were first given practise in making the essential parts of the joints on short pieces of cable and were then required to perform the more difficult operations in a manner acceptable to the supervising engineer and finally to make one or more complete joints.

One of the outstanding features in the construction of both the Pirelli and the General Electric joints was the care used to keep moisture out of the joint. To accomplish this, two small hot air electric blowers of the hand hair dryer type were arranged so as to direct a blast of hot air on the joint from the time the lead sheath was removed until the sleeve had been placed on the finished joint.

Each splicing gang was equipped with a dust ring which was put in place at the manhole before beginning work to keep street dust and dirt from blowing into the manhole during the making of the joint. Although joints were not started during the rain, it sometimes happened that it began to rain during the splicing operation, and for this reason each splicing gang was equipped with a tent which could quickly be placed in position over the manhole. Plastic roofing cement was also supplied with which the dust ring was set into the manhole in order to prevent water entering from the street.

Upon completion, each joint was tested for tightness by applying a pressure with carbon dioxide gas. A soap solution or a heavy oil was placed on the wipes to give an indication of any leaks or porosity. Some of the first wipes made were found to be porous, but after some experimenting it was discovered that by adding pure tin to the solder, and glazing over with a blow torch, tight wipes invariably resulted.

Two splicers were required in the manholes to build a joint. On the General Electric joint, the splicers performed the taping operation in relays, while on the Pirelli joint during taping, one splicer worked at each end. The time required to construct a permanent joint was about eight and ten hours for the General Electric and Pirelli joints, respectively. The time for making the provisional joints was about six hours.

Before splicing operations were started on either the Pirelli or General Electric cable, it was necessary to make special arrangements to provide energy for light and power, which was required along the line for making the joints and evacuating the cable. In Chicago the necessary power was readily obtained by the installation of service cables in the vacant ducts along the line, but in New York this was not feasible and it was necessary to use portable storage batteries and gasoline-engine-driven generating units.

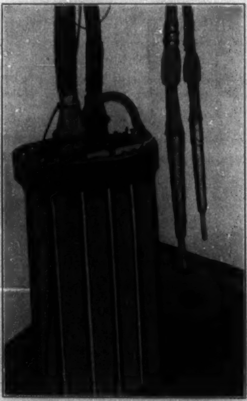

FIG. 35—STOP-JOINT AND PREPARED CABLE ENDS

*Stop-Joint Installation.* The stop-joint was first lowered into the pit in the floor of its manhole, after which the cable was carefully trained so as to leave the ends nearly perpendicular over the stop-joint cover. The ends of the cable were prepared as for an ordinary joint and the special contact terminals sweated to the two conductors. The protective caps were then removed from the porcelain tubes of the stop-joints and the stop-joints were lifted upwards into place, while the cable ends were slipped into the porcelains until they made contact with the spring terminals at the bottom of the porcelain tubes. The cable was then given its final training and wiped at the stop-joints.

The right hand portion of Fig. 35 shows a stop-joint lowered into its pit with the prepared cable ends in position just above it.

Special care was used in the stop-joint manholes to so train and secure the cables that any motion due to heating and cooling would not result in bending the lead sheath at the wipes at the top of the joint.

*Installation of Feeding and Pressure Tanks.* In order to avoid injury to the thin collapsible plates used in the feeding tanks, it was necessary to use great care in first lowering the tanks into the manholes and then raising them to hang from the I-beams in the roof.

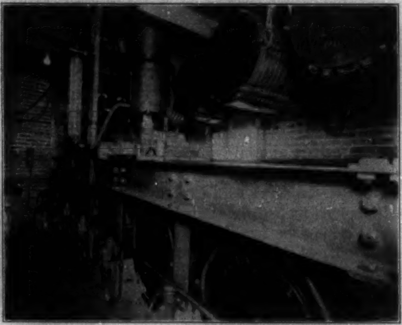

Fig. 36—Feeding Tanks in Position

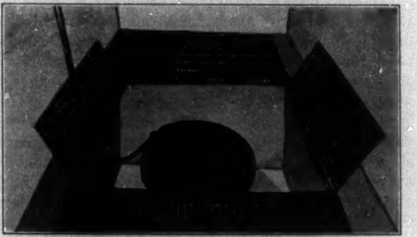

Fig. 37—Pressure Tanks in Position

Fig. 36 shows an installation of feeding tanks in a tower.

The installation of the pressure tanks presented no particular difficulties; they were simply lowered into position in the bottom of the manhole; see Fig. 37.

A typical stop-joint installation, with feeding and pressure tanks and oil pipe lines, is shown diagramatically in Fig. 28.

*Installation of Valves and Oil Lines.* The oil lines used for the various connections between tanks and cable were of three different types; bare lead pipe which was used mainly for connections to joints and valves, jute-covered lead pipe which was used for connections between valves and feeding tanks, and steel wire armored lead pipe which was used where the oil line was pulled in ducts. A typical installation of oil pipe line and valves can be seen in Fig. 28.

*Installation of Terminals.* All of the Chicago terminals are of the General Electric type, but in New York, Pirelli terminals were used on Pirelli cable and General Electric terminals on General Electric cable. Drawings of the two types of terminals are shown in Figs. 19 and 20.

*Oil Conditioning Equipment.* The oil used in impregnating the cable and filling the hollow core, feeding reservoirs, pressure reservoirs, stop-joints, and terminals was the same as was used in the factory for the original cable impregnation. It was developed under the supervision of the Pirelli engineers to meet their especial requirements as to dielectric strength, viscosity and flow point. The oil used has a flow point of minus 15 deg. cent., or lower, which insures proper functioning of the oil in all underground portions of the cable, and special heaters have been installed to care for those portions of the oil system which may be exposed to temperatures below the flow point. The oil pipe runs from the tank towers to the terminals in both New York and Chicago are boxed in and may be heated when necessary from the heaters which are installed in all the tank houses.

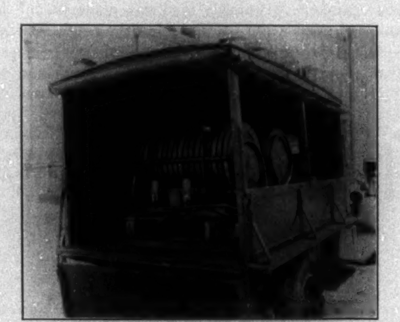

Fig. 38—Transporting Treated Oil

Before any oil was used for filling the central core of the cable, joint casings, or oil tanks, it was necessary to submit it to a special treatment to remove all moisture and dissolved gasses.

In Chicago the towers provided convenient locations for the installation of this oil treating equipment, but in New York it was necessary to install a central oil conditioning plant and transport the treated oil from this point to the various reservoir manholes. Standard feeding reservoirs mounted on trucks were used for this purpose; see Fig. 38.

*Cable Evacuation and Impregnation.* As a preliminary, the engineers who were to perform the major operations required during evacuation and impregnation were given special training. The training in Chicago was greatly facilitated by the use of a dummy set-up, representing a mile section of line, consisting of several short lengths of cable with high and low spots, and connected by glass tubing so that the men could see what was happening. In order that the men could become familiar with field operations, the apparatus which was actually to be used was connected to the ends of the set-up as shown in Fig. 39.

The cable was impregnated one section at a time, the first step being to evacuate and fill the reservoirs with oil, after which the cable was put under vacuum by means of vacuum pumps connected at each provisional and stop-joint on the section. This evacuation was maintained for approximately 12 hr. for drawing out any gas or surplus oil in the core of the cable.

As shown on the profiles, there were many high and low points along a section of line; and slugs of oil were formed at the low points, while gas would collect at the higher points. A suitable test was made at the beginning of evacuation to determine the height of these slugs opposing vacuum between adjacent provisional joints. The maximum and average heights for the slugs were, respectively, 10 and 3 ft. This "slug" test served also as a check on the continuity of the cable core and connections and permitted a prompt discovery of leaks or stoppages.

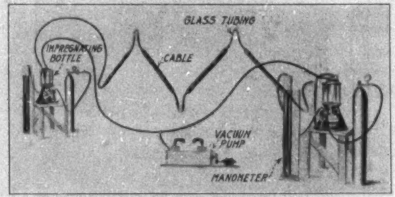

Fig. 39—Dummy Impregnation Set-Up

After the initial 12-hour evacuation period, tests were made to determine if slugs of oil still existed in the low points of the line which would interfere with obtaining a satisfactory vacuum at all points of the section. After these tests proved satisfactory, the line was evacuated for approximately 36 hr. If a good vacuum was then maintained and no leaks occurred, treated oil was admitted to the line.

At the beginning of the impregnation of a section, oil was admitted to only one phase, the second phase being connected when the first was about one-third filled, from 8 to 24 hr. later, depending upon the flow of the oil and the contour of the section. The third phase was connected when the second was about one-third filled. Upon the arrival of the oil at each provisional joint, it was first drained off into test bottles for testing and then the oil was allowed to flow into the impregnating bottle until the flow reached a satisfactory value. After the pressure of the oil had become greater than atmospheric, the apparatus was disconnected and the joint closed.

Because of the difference of line contour and location of feeding tanks, the process of evacuating and impregnating the cable differed somewhat in the two cities. In New York the treated oil was admitted directly to the line from the transportation tanks, which were connected to the cable at the stop-joint manhole located at the high end of the section, while in Chicago it came directly from the conditioning plant in the tower.

In Chicago and at the Dunwoodie tower in New York, on account of the possibility of leaks in the potheads or piping which would let in air at the time of impregnation, the oil was fed from the reservoir floors in the towers to the first manhole of each section; then the oil would feed not only forward into the cable but backward into the pothead and the vacuum maintained ahead of the oil would draw out any air which might come in through possible leaks.

In both New York and Chicago, the rate of oil flow was hastened by heating the conductor with low-voltage current when the low temperatures unduly increased the viscosity of the oil. On some sections in New York, accelerated flow was obtained by feeding in the oil at a provisional joint after the incoming oil had passed that joint. When the cables had been filled with oil and the provisional joints sealed, the valves connecting the reservoir tanks were opened.

From a knowledge of the cable temperature, oil viscosity, pressure heads, and cable profile, it was possible to predict approximately the speed of oil flow along the cable core, and thus to have engineers available for supervision at the provisional joint manholes when the oil arrived at these locations.

The time for evacuation and impregnation of a section varied from four to six days. The cable was then allowed to stand for two or three days before being given an impregnation test. The details of this test have already been described and characteristic results of the tests are shown in Fig. 12. If this test proved satisfactory, the provisional joints were opened, the flow of oil was stopped by inserting the screw in the hole in the connector, and the taping of the joint was completed, converting it into a permanent joint.

*Joint Impregnation.* After a section of the line had been impregnated and the temporary joints converted into permanent joints, the next operation to be performed was the impregnation of the joints. The General Electric and the Pirelli joints required two different methods of treatment.

The Pirelli joints were given an initial heat by means of special electric heating pads supplied from a battery on the truck where other electric power was not available. After the joints had been evacuated, oil was admitted from a special feeding tank.

The impregnation of the General Electric joints required no heat treatment and consisted only of a comparatively brief vacuum treatment and filling.

After the Pirelli joints had been impregnated, they were immediately reinforced with copper bands which were wiped on as a reinforcement for the lead sleeve against the internal oil pressure.

A good idea of the time required for the various processes described is given in the "Progress of Work" diagram shown in Fig. 40.

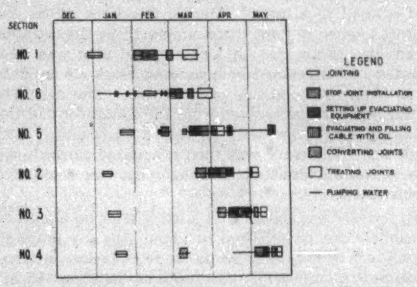

FIG. 40—"PROGRESS OF WORK" DIAGRAM—CHICAGO

*Bonding.* As originally planned, the two lead sheaths of the 132,000-volt cable were to be insulated from each other. It was actually found, however, that in many cases these leads were in contact after the cable had been pulled into the ground. For this reason and also because there was a possibility of dangerously high induced voltages if the outer lead were left floating, the two sheaths were wiped together on each side of each joint. In Chicago, the three cables also were solidly bonded in each manhole. With this bonding, the sheath current is about 50 per cent of the current in the copper and the sheath losses nearly equal the copper losses.

In New York the sheaths of the three cables were bonded at about 1000-ft. intervals in certain straight joint manholes, selected from an electrolysis survey of the line, but in all stop-joint manholes they were bonded on each side of the stop-joint and the two bonds connected.

*Transposition.* In Chicago, the 6-mi. underground line is in series with 30 mi. of overhead line; that is, the cable has only a small percentage of the total impedance of the tie line; therefore it was practicable to install the underground cables without transposition to balance the impedance of the phases. In contrast, the cable in New York formed the entire tie line and, therefore, to obtain equal impedances of the phases, they were transposed at eight points along the line.

*Fireproofing.* The final operation was to give the cables a fireproof covering in the manholes. In Chicago, this consisted of a layer of $\frac{1}{8}$-in. asbestos tape applied with a butt lap, over which was the usual rope and cement fireproofing. The tape was applied because the lead sheaths were so thin it was considered best to protect them against any damage that they might suffer from cracking of the cement or breaking it off, should such a step be necessary for repairs.

The New York companies used their usual type of fireproofing, consisting of metal lath and cement on the greater portion of the line; and a new type consisting of an asbestos netting and special fireproof cement on the balance.

*Testing Set.* Each utility has purchased a special 400,000-volt, 0.25-ampere, direct current, Kenotron cable testing outfit, installed at Hell Gate and Northwest Stations in buildings constructed especially to contain them; see Fig. 41.

These sets are the largest ever made up for commercial use and a minimum space 30 ft. by 30 ft. by 30 ft. is needed for the set alone, exclusive of that required for cable terminals, switch gear, etc. For the purpose of assisting in the location of any failures that may develop during tests or operation, the Kenotron tubes have been arranged so that they may be connected to give higher currents at lower voltages, the maximum current rating being two amperes at 50,000 volts.

The test agreed upon, of 300,000 volts for 15 min., was applied to each phase separately without breakdown or indication of weakness in either the New York or Chicago cables.

FIG. 41—KENOTRON TESTING SET—CHICAGO

## OPERATION

There have been no electrical troubles from the time the cables were put into operation, June 2 for Chicago and August 9 for New York, to the time of writing, October 20; but there have been oil leaks which required repairs in stop-joint, gasket of pothead, joint wipes, pressure tanks, and lead jacket of cable section. In all cases, it has been possible to maintain the line in service until convenient to take it off for repairs.

The maximum load on the lines has been about 45,000 kv-a. The manufacturer's guarantee included a maximum allowable copper temperature of 65 deg. cent., a maximum power factor at that temperature of 1.25 per cent and a carrying capacity of 91,000 kv-a. The insulation of the cable as delivered, however, had a power factor of 0.5 per cent which permits an increase in the rating under identical field conditions to 98,000 kv-a.

The charging current of the underground line is 2400 kv-a. per mi., or about 25 times the value for a 300,000-cir. mil overhead line of the same voltage. The underground installation in Chicago is equivalent to a synchronous condenser of about 14,000-kv-a. capacity and the corresponding figure for New York is 28,000 kv-a.

*Inspection and Signaling.* Special equipment, processes, and plans are being worked out and special crews of men have been selected and trained to locate and repair any failures that may occur. Regular routine inspection is being made of the feeding reservoirs and of all manholes and the quantity of oil in the feeding reservoirs and water conditions noted and recorded and any unusual conditions reported at once.

The lines are provided with the usual automatic switches to open in case of failure and additional devices will be provided to indicate oil leaks as the life of the cable is brief, if it is not entirely filled with oil.

*Repairs.* As the cable has a hollow conductor filled with a very fluid oil, special provisions have been made for repairing the line so as to reduce, as far as possible, the entrance of air and moisture if the oil runs out. Experience indicates the feasibility of confining the damage occurring in this manner to the length of cable on which the trouble occurs, provided that the devices for indicating loss of oil are reasonably accurate and reliable. When necessary to remove and replace a length of cable, arrangements can be made by suitable connections so that there will be a continuous but slight flow of oil out of the cable, thus preventing the ingress of air or moisture. The plan of operation and the details of the devices and methods to be used for this purpose had been discussed at some length by the representatives of the several companies, and a leak in the cable sheath which developed about two weeks after the New York cable was placed in service gave an opportunity to try out these plans. The periodic inspections of the oil reservoir tanks showed that there was a loss of oil at a slow rate on one phase of a section and by inspecting manholes a location was found where oil was leaking out from between the inner and outer lead sheaths on a length of cable. The oil leak was very small, about five cu. cm. per hr., and the cable could have been left in service for weeks if necessary, but it was decided to replace the section promptly.

The static oil pressure on the defective section was about 30 lb. per sq. in. and the change was accomplished with the loss of only a few gallons of oil and without permitting air to enter the good cable on either side of the replacement.

The oil core of the phase to be repaired was connected at the end of the section remote from the feeding reservoirs to the oil core of an undamaged phase thus allowing a continuous flow of oil from both directions toward the repair during all subsequent operations.

The length of cable to be removed was then cut in both manholes so as to leave the joints connected to the two good ends.

Each joint was then taken down by unwiping the lead sleeve and removing the applied insulation and a hole was drilled transversely through the connector and reamed to a taper. During these operations the oil was allowed to flow, thereby preventing the entrance of air into the cable. A long tapered plug was then inserted in the reamed hole so as to block off the flow of oil from the good side of the cable. The defective length was then unsweated from the connector and the replacing length sweated in, and a provisional joint made up. The cable was then evacuated through the two joints, oil admitted, and the joints converted into permanent joints.

Experience has shown that a leaky wipe on a joint in a manhole can be repaired in about 2 hr. by draining the oil out of the joint so as to remove the internal pressure. A stop-joint was replaced in about 15 hr. and a section of cable in 2½ days. It is thought that a failure in a joint which does not involve replacement of cable can be made in approximately 36 to 48 hr. If the trouble or the replacement of the length of cable involves the entrance of a large amount of air into the cable, then it may be necessary to repeat the original process of evacuation and impregnation, requiring considerably greater time.

The time for all of these operations, however, will vary, depending on the location of the trouble and the profile of the section.

*Conclusion.* From the foregoing details it may be seen that many vital features employed in the manufacture, installation, and impregnation of this type of cable will also impart a new direction to the attainment of better and more reliable cables of the ordinary type. The indications are that this cable marks a new epoch in cable engineering.

## Discussion

**H. L. Wallau:** This development marks a substantial advance in the art. From the design data submitted by Emanueli in the maximum working stress appears of the order of 160 kv-in. (63 kv-cm.)—over three times the safe limit set by Shanklin and Matson in 1919. This value assumes non-graded insulation of uniform specific inductive capacity.

Two years ago the speaker made a study of the probable dimensions of single-conductor paper-insulated cables of the ordinary type for use at a maximum potential of 80 kv. to sheath. Maximum working gradients of from 50 to 150 kv-in. were used and the $R/r$ value of the cables set at 2.72. A lead sheath of 9/64-in. thickness was assumed. Typical results were as follows:

| Maximum Working Stress, Kv-in. | $r$ Inches | $R$ Inches | Overall Dia. Inches | Safety Factor |
|---|---|---|---|---|
| 50 | 1.600 | 4.33 | 8.94 | 5.30 |
| 100 | 0.800 | 2.17 | 4.62 | 2.65 |
| 150 | 0.533 | 1.45 | 3.19 | 1.77 |
| The Pirelli cable yields | | | | |
| 160 | 0.610 | 1.315 | 3 approx. | 3.5 to 4<br>From tests |

The safety factor of a cable may be defined as the ratio of the indefinitely sustained breakdown voltage to the operating voltage, or

$$\text{S. F.} = \frac{\text{Breakdown voltage}}{\text{Operating voltage}} = \frac{\text{Breakdown gradient}}{\text{Operating gradient}}$$

Except in the case of Pirelli cable, the numerical values given were obtained by using a sustained breakdown gradient of 265 kv-in. for impregnated paper insulation, based on test data by Peek.

This study led to the conclusion that for such cables working stresses of 150 kv-in. were required since they alone yield cables of reasonable diameter and weight. The danger lay in the low safety factor obtaining.

The test results on the present type of 132-kv. cable reported by W. S. Clark indicate a sustained breakdown voltage of some 260 kv. to 300 kv. or a safety factor of between 3.5 and 4.

This increase in safety factor has apparently been accomplished by two means:

1. The insulation seems to have been graded, not by using different impregnating compounds and one quality of paper but by a reversal of this method, which lends itself particularly well to commercial production, namely, the use of a single compound and of several qualities of paper. Is this supposition correct? What is the calculated maximum working stress in kv-in?

2. Ionization has been practically suppressed by the complete exhaustion of all gases from the cable after installation, the filling of all voids within the cable with suitable oil and by maintaining that condition over the working cycle of the cable, coupled with an internal pressure head, never less than atmospheric, which prevents the entrance of air or moisture.

Incidentally, these cables are guaranteed to operate at a temperature of 65 deg. cent. or 5 deg. higher than the "maximum safe temperature" set up in the A. I. E. E. Standards No. 30. The speaker was instrumental in having the old rule of $t$ = 85 deg. − $E$ modified and suggests that the new standard be further revised to make it accord with present practise.

The reasoning and methods employed leading to the determination of the locations of feed and pressure tanks are exceedingly ingenious and the field impregnation test equally so.

The two types of joint used differ in details. It is interesting to note that machine wrapping is being used in the Pirelli joint and a copper instead of a lead sleeve used in the General Electric joint. It is believed that the Cleveland 66-kv. joint was the first in which either of these two things was done, brass, instead of copper sleeves, being used in Cleveland.

Mr. Torchio has dealt somewhat with the economic aspect of this development, but has not touched on cost. It is rumored that these initial installations are more costly per kv-a. than 66-kv. circuits including 2-to-1 stepup transformers. It is possible that future installations will decrease in cost somewhat, and possible also that for higher-voltage circuits the cost per kv-a. may show an appreciable reduction over that for 132-kv. circuits. Comparisons of cost per kv-a-mi. for voltages of 132-kv. and 220-kv. would be of interest.

There are two points relating to details that are not quite clear. How is the core of the heated cable exhausted? Mr. Clark states that the ends of the cable section are sealed after heating and insulated leads brought out through the seals, after which the vacuum is applied.

In the paper descriptive of the installation methods occurs the statement: "The oil core of the phase to be repaired was connected at the end of the section remote from the feeding reservoirs to the oil core of an undamaged phase, etc." Does not the making of such a field connection require the opening of a joint in one of the undamaged lines?

**H. L. Wallau** (communicated after adjournment): The tabulation given in my previous discussion may be extended to cable for operation at 220 kv. (nominal) using the same $R/r$ ratio. In this case, the voltage between conductor and sheath will be 133.5 kv. allowing the conventional 105 per cent of nominal pressure as maximum circuit voltage.

| Maximum Working Stress, Kv-in. | $r$ Inches | $R$ Inches | Insulation Thickness Inches | Over-all Diameter, 9/64-in. sheath |
|---|---|---|---|---|
| 150 | .891 | 2.42 | 1.53 | 5.12 |
| 160 | .834 | 2.26 | 1.43 | 4.80 |
| 200 | .678 | 1.84 | 1.16 | 3.96 |
| 250 | .534 | 1.45 | .92 | 3.18 |
| 300 | .445 | 1.21 | .77 | 2.70 |

It is fair to assume that manufacturers today cannot produce oil-filled cable which may be operated at a maximum gradient exceeding 160 kv-in. with the factor of safety now believed necessary for such important service, involving powers of the order of 150,000 kv-a. per circuit at 220 kv. Factors of safety are measures of ignorance. Hence, operating experience with the 132-kv. cables may disclose that a factor of safety of from 2 to 2.5 is quite liberal, which would permit of gradients of the order of 250 to 300 kv. per in. Such gradients would bring 220-kv. cables in the 3-in. diameter class.

Mr. Roper has stated that the Chicago installation cost complete including conduit, cable, towers, tanks, etc., is $1,250,000 for a 6-mi. line of 98,000 kv-a. capacity. This yields a cost of $2.13 per kv-a-mi. If experience proves that this cable might safely be operated at 220 kv. with the same ampere loading or 163,000 kv-a. the cost per kv-a-mi. would be reduced to $1.28. The cost of the 66-kv. cable installation in Cleveland, complete in every detail, based on a conservative rating of 35,000 kv-a. per circuit, is $1.62 per kv-a-mi. Two circuits each 8¼ mi. are installed.

**F. A. Brownell:** The cable installations in New York and Chicago have shown a great advancement in the art of underground transmission. Apparently we will have to change our concepts regarding high-tension cable, both in regard to cost and installation, for it is quite obvious, after witnessing the moving pictures of the installations, that the cost must have been considerable.

Mr. Emanueli, in a footnote, mentions "all the delicate operations of installation and impregnation." That "delicate operations" is a new term to most of us. Ordinarily we do not think of delicate operations in connection with cable installation but if we did we might lessen some of our troubles.

The following statement seems rather startling, "All these difficulties and uncertainties would not have allowed the design of a 132-kv. cable of the usual type with any probability of success."

It would be interesting to know whether or not the American cable engineers are in agreement with this statement as some of the preliminary tests made on the usual type of cable have been encouraging.

**J. B. Whitehead:** Mr. Clark has mentioned the electrical characteristics of these cables. He stated that he had found a descending power-factor-voltage curve indicating a negative ionization coefficient, and that this fact caused him and his associates some disquiet, because they saw no obvious explanation. Having visited my laboratory in Baltimore and learned that we too had found such curves, he was somewhat relieved, but not yet satisfied. He then stated that he subsequently found that the explanation of his descending power-factor-voltage curves was found in an error introduced into his air condenser, owing to the high moisture content of the air; and that having eliminated this source of error he found that his power-factor curves came back to a flat shape, thus indicating that he attributed the apparent descending power-factor curve to an error in his method of measurement. He did not tell you, however, what he thought of our descending power-factor curves, but the obvious inference is that he attributes them to a similar source of error. I want to correct that impression.

It may be true that in the presence of moist air, that is to say, a relative humidity of about 80 per cent, an open-air condenser may take on a power factor which is other than zero. If it does, and incidentally I doubt it, such an error will cause a decrease in the apparent power factor of a cable measured in the Schering bridge in the usual connection. However, the apparent decrease of power factor owing to such an error is not nearly as great as the decrease that may be observed under certain conditions in the power-factor-voltage curve of perfectly impregnated insulation.

We have found dozens of such decreasing power-factor-voltage curves. They are inherent in all thoroughly impregnated insulation when the temperature is above 40 or 50 deg. Below this temperature such insulation shows a perfectly flat power-factor curve, but above the temperature mentioned there is a maximum power factor at relatively low voltage gradient, decreasing thereafter towards higher values of gradient.

I believe that there is a sound theoretical explanation of this decrease in power factor. The power factor of impregnated paper insulation is intimately connected with the conductivity characteristics of the impregnating compound. The conductivity of these compounds is due to the motion of ions which probably consist of aggregates of molecules surrounding a central charge of molecular or atomic dimensions. It is well known that this type of conductivity has an initial limiting value at any temperature. As the voltage rises the ions are drawn out of the liquid more and more rapidly until finally the conductivity is greatly lessened, being that corresponding to the rate at which new ions are generated or liberated in the liquid. This conductivity has in general a much lower value than the initial value. Thus as the voltage goes up the charging component of the current goes up, but the conductivity component of the charging current remains fixed and the power factor therefore comes down.

**R. W. Atkinson:** I wish to say a word about a point concerning which Dr. Whitehead has spoken. We have found, as has he, that some types of cable dielectric do show very definitely a decrease in power factor with increasing voltage. Our standard of reference has been an air condenser with a dielectric of compressed gas (very dry, compressed carbon dioxide). Many types of check measurements, carefully repeated at intervals over a term of several years, have given us great assurance in these measurements showing decrease of power factor in certain dielectrics, with increase in voltage.

Our experience as to the type of dielectric most likely to produce this condition is also parallel to Dr. Whitehead's, namely, well impregnated dielectric, tested at high temperatures, that is within the range of 60 to 100 deg. cent. In our case, characteristics of this kind associated with saturated paper have seemed to occur particularly where the impregnating medium is a relatively fluid oil.

No one needs to be told how great is the accomplishment that has been described in this paper. Transmission of power by cables at 132 kv. until so recently the limit of extensive overhead transmission, is recognized at once as a great advance in all electrical industry and can be appreciated by the executive who is concerned with financial problems, by the engineer who is a specialist in some other line, the general engineer as well as by the transmission engineer.

However, many may not appreciate the magnitude of the work done in arriving at this finished result. The authors have been modest in describing the development of this work and have presented to us a finished product, a procedure that always makes an accomplishment seem easy.

Aside from those taking part in this particular development or directly associated with it, only those who have had to cope with related problems can adequately appreciate the magnitude of the physical task performed. I want, therefore, to congratulate these men and the manufacturing and operating companies they represent, for their great vision as well as for their painstaking efforts in overcoming the obstacles in the way of accomplishment.

**W. A. Del Mar:** There is one aspect of the installation which especially interests me as a cable manufacture, and that is to see these two manufacturers, the General Electric and the Pirelli Companies, undertaking the major part of the engineering work. I do not mean to belittle what has been done by the operating companies, but we have been seeing a growing tendency, in recent years, toward the operating companies taking over more and more of the design details of cable installations. Here we have a return to the practise of leaving the major responsibility to the cable manufacturers, which I think is a healthy sign.

The manufacturers appear to have taken this responsibility with a full appreciation of the difficult and intricate engineering features involved and they are to be congratulated on having produced a model installation.

We are, however, only at the threshold of 132,000-volt cable developments and it may be found that many of the complications are unnecessary. There are at present, both at Chicago and Newark, experimental installations of 132,000-volt cable, some of which are of the ordinary design and they have been successfully carrying voltage for several months.

The question of the breathing of the cable, that is to say, the expansion and contraction of the oil in and out of the cable, is, of course, a very important feature of the installation. It would be interesting to know whether this expansion, which forces oil from the cable into the reservoir, is of the magnitude to be expected from the expansion of the oil in the hollow core only, or whether the expansion is greater than that and involves part or all of the oil which is with the paper.

Mr. Emanueli's paper bases the theory of this installation upon the idea of maintaining constant the impregnation of the cable by providing for the effects of changing temperature. We should not forget that it also involves the maintenance of a certain variable hydrostatic pressure within the cable which, according to this paper, varies from 1 to, I think, 3 or 4 atmospheres, so that probably the cable, during most of its operation, is at considerably above atmospheric pressure. The dielectric strength of the insulation, and its capability of resisting ionization are greatly increased by the hydrostatic pressure. Possibly in going to higher voltages, which I think we can see clearly before us now, that aspect of the design will have to be given more consideration.

**F. M. Farmer:** The essential feature of this type of construction, of course, is the application in as nearly an ideal way as possible of the theory which has been recognized for a long time as being essential in insulation, namely, the complete removal of gas and voids from the insulation (which means in the case of cable insulation not only the complete removal of gas and voids from the paper but also from the oil) and the maintaining of this condition under all conditions of operation. In other words the complete insulation structure must be kept in its proper condition at all times.

It is evident, of course, that this construction must have been expensive. There might be some question in the minds of some operating men as to the economic justification for these installations—some question whether the present state of the art justifies the expenditure involved. I think we ought to look just a little ahead.

If this type of construction proves successful, and the chances seem to be excellent that it will, it demonstrates in the first place that there probably is no reasonable limit to the voltage at which underground transmission can be made. Two hundred and twenty thousand volts is obviously in sight under those conditions, and the economic phase of the situation then takes on an entirely different aspect. Costs that might not be justifiable at 133 kv. might be entirely at 220 kv.

In the second place, if this principle is shown to be the solution of the high-voltage cable problem, won't means be found for applying it at moderate voltages at considerably less expense? So I say that this large-scale experiment, as it might be called, is going to be of real value in demonstrating the correctness of this fundamental theory. Despite the fact that this theory has been with us a good many years, there have been conflicting evidences as to its importance. This installation is going to demonstrate once and for all the soundness of that fundamental theory. If the theory is proved then the expenditure on the part of these two companies will be amply justified, and as some of the speakers have said, the industry will owe these companies a great debt, for their foresightedness and their courage in going ahead with this very expensive undertaking.

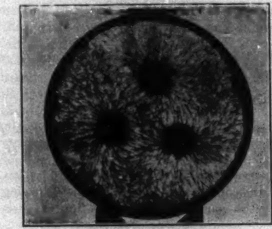

FIG. 1

**E. B. Meyer:** I might say that in the Public Service System of New Jersey there is an experimental installation of a 132,000-volt cable. The cable was furnished by three manufacturers, and each manufacturer was allowed, in designing the cable, to bring forth his own ideas, each type of cable being one phase of the circuit approximately 1000 ft. in length, a total of 3000 ft. of cable. The cable is constructed somewhat on the order of cables operating at lower voltages.

One cable is a hollow-core type filled with compound, another of a concentric type, and still a third one has a rope core. The cables are not oil-filled. The joints are both machine-made and hand-wrapped, using paper and varnished cambric. The cable has been under potential since February of this year, and on June 1 it was placed in service carrying load.

**C. F. Harding:** Following the suggestion of Dr. Whitehead, not only does that field of intensity change very greatly within the dielectric with the change of voltage, but it departs materially from any calculated field which would be expected in a single-phase cable, and particularly in a multiple-conductor cable.

The accompanying illustration is a photograph of this field in a cable model. In the methods which have been used in this particular demonstration,[1] not only is the field, and therefore the intensity, about the surface of the conductors at different points very greatly changed with increased voltage but we also have a sufficient mechanical moment in the dielectric to produce an actual rotating field.

We wondered at one time what that blur on the photograph was, and what the apparent difficulty in visualizing the field might be, but after inspecting carefully and taking several photographs the cause was found to be the actual rotating of the particles in the dielectric itself, in the multiple-conductor cable.

Such a method of visualizing and analyzing the dielectric field by photographic means, possibly with the motion picture camera, applied to the actual motion within the dielectric at higher voltages, may throw some light upon the test values, maintenance costs, and possibly the cause of breakdown of such high-voltage cables.

**G. B. Shanklin:** The principle of a liquid-oil filler to prevent void formation in high-tension fibrous insulation is so firmly established and has such preponderant evidence back of it that little need be said here.

To my mind, the most convincing evidence is found in the evolution of high-voltage capacitors for power-factor correction. For reasons of economy it is necessary to operate the dielectric in these capacitors at a working stress several times higher than that in cables of the ordinary type. Every conceivable form of insulation was tried, no limits being set by mechanical requirements, such as flexibility, etc. Paper, carefully evacuated and impregnated with a liquid oil, submerged in this oil and sealed off from the atmosphere, proved to be in a class by itself. No other form of dielectric could even approach it from the standpoint of economy and safety.

To work out and apply these principles in a practical way to a long line of 132,000-volt cable was a vastly more difficult job. The papers presented today show how it was done, and to the Pirelli Company belongs the major credit for their initiative and foresight.

It should be remembered that these lines are pioneer installations. Invaluable experience has been gained which will, in future installations, result in very material savings in economy and simplicity.

A great deal of attention has recently been centered upon the possible use of ordinary solid cable, that is, cable impregnated with very viscous compounds, for 132,000-volt operation. I should like to point out that our company was one of the first to attack the problem from this angle. We have had trial lengths of this type of cable operating on the 110,000-volt lines of the New York Power and Light Corporation for more than three years and propose to continue our experiments.

Our present conclusions are simply these. The solid-type cable can be made to operate more safely by oil-reservoir feed from the joints. No doubt the present limit of 66,000 volts can be raised by taking every possible precaution. Whether we shall ever reach successful 132,000-volt operation is very doubtful. If so, one thing is certain, we shall be too near the ragged edge for comfort and cannot hope to approach the operating record of the liquid-oil-filled-cable, with its greater factor of safety, both from the standpoint of voltage stressing and current loading. From an economic standpoint it is my opinion that the liquid-oil-filled high-tension cable will eventually be on equal terms with solid cable of the same voltage rating, due to reduction in insulation thickness and the greater allowable temperature range, or current loading.

Finally, we should look ahead to the future, as Mr. Torchio has so ably pointed out, for the day will come when 220,000-volt cable will be needed.

**K. W. Miller:** In the study of oil movements in single-conductor cable in general as well as in the determination of the lengths of sections of line between stop joints and in the design of the reservoirs, pressure tanks, and cable, it is important to be able to predetermine oil flow and pressure drops along the section during load changes. Since the rate of oil flow depends on the rate of temperature change and since also the friction drop is directly dependent on the viscosity of the oil, which in turn is dependent on the temperature, it follows that from a complete solution of the cable temperature transient under any assumed conditions it would be possible to predict oil flows and pressures with considerable accuracy. Such a solution is possible for the cases of cable cooling after load removal by the use of Bessel functions.

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[1] "Improved Method of Visualizing and Photographing the Dielectric Field," by R. H. George, K. A. Oplinger, and C. F. Harding, *Bulletin* of Eng. Exp. Station, Purdue University.

Mr. Emanueli has derived approximate values for these quantitites which he calls $a$ and $b$ using several simplifying assumptions, and from them determined the general layout of the oil system. The static pressures and the reservoirs are so large that considerable inaccuracies in the determination of oil flows and pressure drops are not very important. However, long sections, oil towers, and high oil pressures requiring reinforced lead sheaths, and causing frequent oil leaks, are all disadvantages that will probably be eliminated on any future lines. With smaller static pressures, the pressure drops with changing load will be more important, and also the pressure drop due to the radial oil flow through the insulation will become relatively more important.

The question of the relative merits of oil core and fluted lead-sheath oil ducts, also requires a more thorough analysis of the temperature transient. Knowledge of this thermal transient is quite important in consideration of voids and compound migration in lower-voltage cables not oil-filled. Therefore, it appears worth while to analyze the thermal transient more exactly.

Let us consider a cylindrical element of insulation of unit length at radius $x$ and thickness $d\,x$. In addition let

$t$ = time in seconds
$r$ = inside radius of insulation
$R$ = outside radius of insulation
$Q_1$ = thermal capacity of copper and free oil per unit length
$Q_2$ = thermal capacity of sheath per unit length
$q$ = specific thermal capacity of insulation per unit volume
$p$ = specific thermal resistance of insulation per unit volume
$E$ = thermal resistance, sheath to duct per unit length (assumed constant)
$T$ = temperature deg. cent. at point considered
$T_0$ = duct temperature—assumed constant over initial period of transient
$W$ = watts heat flow across circular element at $x$
$W_e$ = watts heat flow sheath to duct
$e$ = volumetric thermal coefficient of expansion of oil and paper insulation
$a_1$ = rate of oil flow contributed by core per unit length
$a_2$ = rate of oil flow contributed by insulation
$a_3$ = rate of oil flow contributed by thermal shrinkage of sheath
$a$ = total resultant rate of oil flow, per unit length.

The rate of temperature change in an element of volume $\Delta\,V$ is directly proportional to the heat generated in the element, to the differential of heat entering and leaving the element, and inversely proportional to the heat storage capacity of the element. Setting up this relation and simplifying we get

$$2\,\pi\,q\,\frac{\partial\,T}{\partial\,t} = -\,\frac{1}{x}\,\frac{\partial\,W}{\partial\,x} + \frac{k\,(D.\,L.)}{x^2} \qquad (1)$$

where the last term represents the effect of dielectric loss on the assumption that the dielectric power factor is constant, independent of voltage gradient. Variation of dielectric loss with temperature can be approximated by a method not discussed here.

The differential temperature drop across an element is directly proportional to the heat flowing across the element and to the heat resistivity of the element. Setting up this relation and simplifying we get:

$$\frac{2\,\pi\,x}{P}\cdot\frac{\partial\,T}{\partial\,x} = -\,W \qquad (2)$$

Differentiating (2) with respect to $x$ and substituting into (1)

$$p\,q\,\frac{\partial\,T}{\partial\,t} = \frac{\partial^2\,T}{\partial\,x^2} + \frac{1}{x}\,\frac{\partial\,T}{\partial\,x} + \frac{k\,(D.\,L.)}{x^2} \qquad (3)$$

This equation cannot be exactly solved in general due to the dielectric-loss term. However, for the most important case of dropping both voltage and current this term automatically disappears except for the initial condition where it can easily be handled.

A solution of (3) for opening the switch and "killing the line" which is sufficiently general to satisfy all limiting conditions is

$$T = \sum_{n=1}^{n=\infty} e^{-\frac{u_n^2\,t}{pq}}\,[\,A_n\,J_0\,(u_n\,x) + B_n\,Y_0\,(u_n\,x)\,] + T_0 \qquad (4)$$

where $A_n$ and $B_n$ are not independent.

The limiting conditions in time are

$$t = 0, \quad T = f_1\,(x) \quad (f_1 \text{ known})$$
$$t = \infty \quad T = T_0 \qquad (5)$$

and in space are:

$$x = r, \quad \frac{\partial\,T}{\partial\,t} = -\,\frac{W}{Q_1} \qquad (6)$$

$$x = R, \quad \frac{\partial\,T}{\partial\,t} = \frac{W - W_E}{Q_2} \qquad (7)$$

$$W_E = \frac{T - T_0}{E} \qquad (8)$$

Combining (8) with (7) and then (2) with (6) and (7) we get

$$x = r, \quad \frac{\partial\,T}{\partial\,t} = \frac{2\,\pi\,r}{p\,Q_1}\cdot\frac{\partial\,T}{\partial\,x} \qquad (6a)$$

$$x = R, \quad \frac{\partial\,T}{\partial\,t} = \frac{-\,2\,\pi\,R}{p\,Q_2}\cdot\frac{\partial\,T}{\partial\,x} - \frac{T - T_0}{E\,Q_2} \qquad (7a)$$

Differentiating equation (4) and substituting it into equations (6a) and (7a) and simplifying we obtain the following equations for determining the roots $U_n$ and the relation between constants $A_n$ and $B_n$

$$\frac{-\,B_n}{A_n} = \left[\frac{M_1 - \phi\left(\frac{r}{R}\,Z\right)}{M_1 - \psi\left(\frac{r}{R}\,Z\right)}\right]\theta\left(\frac{r}{R}\,Z\right)$$

$$= \left[\frac{M_2 + \phi\,(Z) - \frac{N}{Z^2}}{M_2 + \psi\,(Z) - \frac{N}{Z^2}}\right]\theta\,(Z) \qquad (9)$$

where $M_1 = \frac{Q_1}{2\,\pi\,q\,r^2}$, $M_2 = \frac{Q_2}{2\,\pi\,q\,R^2}$, $N = \frac{p}{2\,\pi\,E}$

and

$$\phi\,(x) = \frac{J_1\,(x)}{x\,J_0\,(x)},\ \psi\,(x) = \frac{Y_1\,(x)}{x\,Y_0\,(x)},\ \theta\,(x) = \frac{J_0\,(x)}{Y_0\,(x)},\ Z = R\,u$$

Equation (9) may readily be solved graphically for the first three roots $Z_n = R\,U_n$. Since the time exponents in equation (4) vary as $(u_n)^2$, the series rapidly converges for all except very short times. But for zero time, knowing copper loss, dielectric loss, sheath loss, and $f_1\,(x)$, the temperature derivatives can be obtained directly from equations (3), (6), and (7). Therefore, the first three terms will give ample accuracy.

Values of the constants $A_n$ can be determined by equating equation (4) equal to $f_1\,(x)$ at time $t = 0$ and giving $n$ fixed values to $x$ and solving for the coefficients $A_n$. The nature of the Bessel functions is such that $f_1\,(x)$ can be closely approximated with three terms. Equation (4) is now completely determined.

If we take the time derivative of equation (4), we may multiply it by the elementary volume and by the unit volumetric coefficient of shrinkage for the insulation and integrate for the total oil demand of the insulation.

$$a_2 = \int_r^R -2\pi\epsilon\left(\frac{\partial T}{\partial t}\right) x\,dx$$

$$= \sum_{n=1}^{n=\infty} \frac{2\pi\epsilon}{p\,q} e^{-\frac{u_n^2 t}{pq}} \Big[ A_n (u_n x) J_1 (u_n x)$$

$$+ B_n (u_n x) Y_1 (u_n x) \Big]_r^R \qquad (10)$$

If we let $x = r$ and $x = R$ in equation (4) we get the thermal transient of the copper and sheath respectively. The time derivative of the equation for $x = r$ can be multiplied by the thermal volumetric expansion coefficient of the copper and oil in the core to obtain that portion of the oil flow $a_1$ contributed by the oil in the core. Likewise the time derivative of equation (4) for the sheath when $x = R$ can be multiplied by the linear coefficient of thermal expansion of lead, properly applied, to obtain the volumetric shrinkage of the sheath, $a_3$. Then the total oil flow is $a = + a_1 + a_2 - a_3$.

It is interesting to note in the numerical application of these equations that with low dielectric loss and large sheath loss, or also for dropping load current only, then during the initial period the sheath shrinkage may be nearly equal to the volumetric shrinkage of the oil. For these conditions in extreme cases the oil flow $a$ at time $t = 0$ may start at zero or even a negative value (reverse flow).

A remaining consideration is the natural elasticity of the cable. If we assume perfect impregnation it may be shown that with any reasonable assumption for the volumetric coefficients of compressibility of the oil and solids and of Young's modulus for the lead sheath and copper binding ribbon, that the elastic effect cannot possibly exceed the equivalent of 1 deg. cent. for the pressure changes involved. As 1 deg. cent. is only a few per cent of the maximum total temperature change of the cable for any condition, the elastic effect may be neglected without serious error.

Knowing the copper temperature transient (and with it the oil viscosity), the resistance coefficient which Mr. Emanueli calls $b$ is known as a function of time. Therefore, the product $a\,b$ or pressure drop can be completely determined with the same accuracy as we can measure the various constants of the cable.

The oil system was designed to maintain the oil pressure in the central core above atmospheric pressure. However, it must be remembered that capillary forces are very considerable and the paper fibres having once been "wet" by the oil will draw oil in from the core even though the pressure in the core drops below atmospheric. Radial friction pressure drops are not large so that a considerable margin of safety exists for the prevention of voids. Oil flow as determined theoretically from equation (11) and experimentally in the field, checks within reasonable limits, indicating that no voids form in the insulation during the worst case, that is, killing the line after it has been carrying full load long enough to reach its maximum temperature.

**H. R. Searing:** One discussor asked the question about the paragraph "the oil core of the phase to be repaired was connected at the end of the section remote from the feeding reservoirs," and so forth.

There wasn't any joint opened. The connections were made at the stop joint. When we speak of the end of the section, we mean the far end, down at the stop so that the oil flows down hill on a good phase and back up the hill to the point where the repair is made.

I wanted to bring out a point that has been overlooked in the paper, that is, that the New York line, for instance, has a capacity effect amounting to about 29,000-kv-a., and I wanted to tell what that does to a central station system.

Naturally the major effect would be noticed at times of lightest load. It isn't predominant on the peak. These figures are for 4:00 a. m. in the winter when there isn't the ice-manufacturing load that we have in the summer. With a system load of 75,000 kw. before cutting the line in, the system power factor is 70 per cent, and after cutting in the line it goes to 80 per cent. The operating man will appreciate what that means on station economies. That is only one line.

What is going to be the result if you have ten lines such as that?

The second thing to point out is that with a nominal bus voltage of 13,800, if on cutting the line in you don't at the same time run the field rheostats down, the voltage at this time of morning goes to 14,600, and in cutting the line out from a nominal bus of 13,800 the voltage drops to 12,900. Voltage regulation of that character isn't a pleasant thing to deal with.

**W. N. Eddy** (communicated after adjournment): Throughout Mr. Emanueli's explanation of the formation of the gas bubbles and films in high-tension insulation, no mention is found of the influence of pressure on the solubility of gases in the impregnating oil. It seems as though this should form an essential part of such a discussion because as long as the air content of the insulation is in solution it is harmless. For instance his second reason for the presence of gas films—that the insulating compound carries in solution a great volume of gas, part of which is set free while the compound is passing through the paper during impregnation—is extremely difficult to accept. Instead, it seems more reasonable and in better agreement with experimental results to consider that when the impregnating compound first fills the paper, its gas content is all in solution, that no gas separates out until the local pressure is reduced by the formation of contraction voids. It is also indicated by results of experimental investigation that a proper impregnating procedure will keep the air content of the paper and compound sufficiently low so that it is not primarily responsible for the formation of bubbles or voids in the insulation.

The development of the oil-filled cable is further evidence that the quality of impregnated paper insulation is not yet limited by the type of materials in use. In attempting to determine how far distant such limits are, it is of interest to consider the dielectric strength of miniature units of the insulation in sheet form submerged in excess compound, as they provide maximum freedom of compound movement and therefore approach what is probably the ultimate quality obtainable with the materials in question. It is encouraging to note that three layers of low-air-resistance paper can be saturated in this form so that they will withstand without failure or any indication of deterioration, a stress of 750 volts per mil for over 18 months, even using compounds no thinner than a heavy cylinder oil.

Both Mr. Clark and Mr. Emanueli mention that while the oil filling does not change the short-time breakdown, it greatly improves the life of the insulation. The following test results (Table I) confirm this in indicating that sheet samples of insulation of the form above referred to, show considerable improvement in short-time breakdown over typical cable insulation but a still greater improvement in life. The figures given for cable insulation are believed representative of the best cables of the usual type now being manufactured.

TABLE I

| | | |
|---|---|---|
| 3-conductor cable | short time breakdown. . . . 407 volts per mil | |
| | life at 75 per cent (305 volts per mil). . . . . . | 0.7 hr. |
| 1-conductor cable | short time breakdown. . . . 480 volts per mil | |
| | life at 75 per cent (360 volts per mil). . . . . . | 5. hr. |
| sheet insulation | short time breakdown. . . 1000 volts per mil | |
| | life at 75 per cent (750 volts per mil). . . . . . | 1½ years |

It is also interesting to note that when this sheet insulation is purposely saturated so as to include bubbles of air, its dielectric strength is reduced 50 per cent, to nearly that of single-conductor cable insulation, while the strength of the separate paper sheets is unaffected, remaining slightly less than the cable insulation.

TABLE II

| Air Pressure above compound during Saturation | Short-Time Breakdown in Volts/Mil | |
|---|---|---|
| | Complete Sample of 3 Layers | Separate Layers |
| 228. Cm. | 590 | 382 |
| 0.02 | 1016 | 381 |

In general the quality of the sheet form of insulation mentioned above is believed to indicate that considerable improvement in impregnated paper insulation can yet be expected before the quality of such insulation will be limited by the type of material in present use.

**Philip Torchio:** Before answering the questions raised in the discussion, it is here recorded that the lines have continued in service to date (December 30) without any electrical failure in cables or joints.

Mr. Wallau has remarked that in dealing with the economic aspects of this development, figures of costs were omitted. The total cost for the New York 12-mi. installation when completed for 98,000 kv-a. will be $4,100,000, or $3.50 per kv-a-mi. The corresponding cost of a 66,000-volt line for 35,000 kv-a. would be $2,200,000, or $5.25 per kv-a-mi.

The total of $4,100,000 includes $950,000 in spare ducts and two terminal buildings, and testing equipment also available for future installations and other uses. The receiving end has double transformation and switches for 45,000 and 13,200 volts. Again, the cable obtained from Milan and the accessories, of entirely new and experimental design, built by Pirelli, had to bear oversea transportation and 35 per cent to 40 per cent import duty. In any future installations all material would be manufactured here, and, in addition, the heavy costs of experiment, research, and development in the factory, and of such extensive technical and research investigations in the field, will not be duplicated.

Any comparison of cost must, of course, take into account the wide differences in local conditions—especially those affecting subway costs, such as surface and subsurface conditions (which conditions undoubtedly greatly influence the comparison between Mr. Wallau's figures and these)—and savings in substation costs, synchronous condensers, transmission and transformation losses, etc., which also vary locally.

The increment cost for an additional feeder would be $1.98 per kv-a-mi. for 132 kv. and $3.00 per kv-a-mi. for 66 kv. All these figures indicate an outstanding economic saving for the 132-kv. cable line.

Even these relative comparisons are only approximately true, as the oil-filled cable can safely carry higher overloads and also is more serviceable in operation because a defective sheath will give a warning long before failure, while in solid-insulation cable it manifests itself by sudden electrical failure. These features may prove to be of definite economic value in enabling one to install considerably less reserve cable capacity than it is now safe to provide in installations using solid-insulation cable.

In New York, a most important consideration was that we should be in a position to receive into the city, when available, considerable amounts of bulk power delivered at high voltage from future water-power developments. The practical solution of this problem was felt to justify the advance investment in a line having a capacity three times larger than required in the very immediate future.

Our experience so far seems to point to the achievement of a new standard in cable operation, indicating the probability that such cable will have a reliability superior to any of the cables for lower voltages with which we have been familiar.

It is gratifying to report such satisfactory and epoch-making results, and to express due appreciation of the vital contribution made by the manufacturers and their engineers.

**A. H. Kehoe:** Mr. Torchio will supply the cost data for the New York installation in his closing written discussion. However, I should like to report that while the investments exceeded the minimum estimates, due to charges for supervision and some special unforeseen equipment, these did not cause our costs to be increased excessively. I believe that with future lines the costs will be scaled down so that even our early estimates will be materially reduced.

**D. W. Roper:** To give an idea of the complexity of the work involved in evacuating and impregnating the line after all the joints are first made up in a preliminary way and after the first section is installed so you then have all processes in progress in the various sections, the maximum number occurs during the evacuating and impregnating process. That takes something like four or five days and is a continuous process 24 hr. per day. The maximum number of men employed on the line in Chicago occurred when this evacuating and impregnating process was in progress on one section, and other portions of the work were in progress on several other sections, at which time the number of men was 125. This included about forty engaged on pumping operations and the representatives of manufacturers.

The total cost of the Chicago line including the conduit, the cable, the terminal towers, the intermediate towers for the oil reservoirs, the Kenotron testing outfit, and a reasonable proportion of the transformers and the terminals at the Northwest station, was $1,250,000.

There have been no electrical failures whatever in either the cable or the joints in New York or Chicago. The troubles have all been confined to oil leaks.

**W. S. Clark:** The reason there was such a large supervision on the part of the manufacturers' engineers in the installation of this cable was that the manufacturers' engineers were more familiar with this new type of cable than were the utilities' engineers. If the installation were repeated in New York or Chicago, the amount of supervision by the manufacturers would be negligible.

# Illinois Central Suburban Service*

## First Year of Electric Operation in Chicago

BY W. M. VANDERSLUIS[1]

Associate, A. I. E. E.

***Synopsis.**—This paper gives operating records of the first year of electrical operation of the suburban service of the Illinois Central Railroad. It shows monthly curves of load, kw-hr. per car-mile, maximum demand, load factor, and temperature. It also shows monthly curves for the last four years of passengers, car-miles, seat-miles, and operating income. The improvements in service are enumerated and the general results at this date are discussed.*

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### STEAM OPERATION

On July 21, 1856, the Illinois Central Railroad started suburban service in Chicago by running four trains each way between down-town Chicago and Hyde Park. It is recorded that the first train to Hyde Park did not carry a single paid passenger.

This service was gradually extended until, in July of 1926, there were in regular operation on each normal week day, a total of 398 trains with service extended to Matteon on the South, to South Chicago on the South Chicago Branch, and to Blue Island on the Blue Island Branch. In the year 1925, this steam service carried a total of 24,000,000 paid passengers. Approximately 285 coaches, mostly of wood construction and with an average seating capacity of 56 persons, were used in this service. About 60 locomotives were necessary for the daily operation.

### ELECTRIC OPERATION

Electric operation for the suburban service has been agitated for years by various civic bodies, and the first formal report on feasibility and costs was made in November, 1909. This was followed by several other investigations and reports, but the railroad did not agree to the project until the passage of the so-called Lake Front Ordinance in 1919. This provided that the suburban service should be completely electrified by February 20, 1927. The commitment of the Illinois Central to electrify its tracks in the City of Chicago was a part of its general agreement with the City of Chicago, the South Park Commissioners and the War Department, covering riparian rights, changes in grades to permit of easy access to the lake front, and changes in property ownership.

On July 21, 1926, exactly 70 years after the first steam service was started, three electric trains were operated each way in the local service between Randolph Street and Hyde Park. It will be noted that the electric service was started seven months before the time called for in the Lake Front Ordinance. The second week 80 trains were operated each day and in the period of about five weeks, the electric service was built up to a total of over 350 trains. These were all operated, of course, on the existing steam time-table, as there was still a considerable number of steam trains in the service.

The first electric time-table was put into effect on August 28th, with a total of 396 revenue trains. On account of a shortage of new equipment it was still necessary to run six trains by steam, but these were confined so far as possible to those carrying shop employes.

To-day, 470 revenue trains are being operated on a normal week day. In addition there are 14 equipment trains and 72 Chicago, South Shore, and South Bend trains, the latter being operated between Kensington and Randolph Street. This is a total of 556 electric trains.

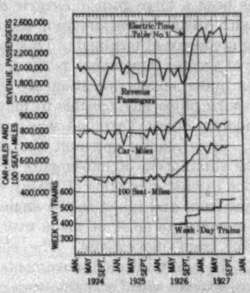

FIG. 1—OPERATING CURVES BEFORE AND AFTER STARTING ELECTRIC OPERATION ON ILLINOIS CENTRAL RAILROAD

These curves show the number of revenue passengers per month, car-miles per month, hundreds of seat-miles per month, and number of week-day trains per day

Electric service was put into effect without any serious accidents or interruptions and has so continued during the first year.

Due to the fact that all of the motor-trailer car units are uniform in design and in operating characteristics, the preparation of time-tables, and the handling of equipment at terminal points has been greatly simplified.

Fig. 1 shows by months the revenue passengers

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*For description of Illinois Central Suburban Electrification, see *Journal of Western Society of Engineers*, March, 1926, Vol. 31, No. 3. *General Electric Review*, April, 1927, Vol. 30, No. 4.

[1] Electrical Engineer, Illinois Central Railroad, Chicago, Ill.

*Presented at the Regional Meeting of District No. 5 of the A. I. E. E., Chicago, Ill., Nov. 28-30, 1927.*

carried, car-miles and seat-miles operated, and the week day trains in service.

### IMPROVEMENT IN SERVICE

Of particular interest is the improvement in running times due to electric operation. The latest electric time-table shows decrease in running times over the old steam service of from 11 to 28 per cent for the various classes of trains, the larger percentages resulting for trains to Kensington and beyond. The decrease in over-all time results from high maximum speeds and by the use of high accelerating and braking rates. Acceleration is at the rate of 1½ mi. per hr. per sec., which is about six times as rapid as that of through passenger steam trains. Under normal operation, a train will reach a speed of 28 mi. an hr. in 20 sec. After that point, the rate of acceleration falls off but on level tangent track a train will reach a speed of 50 mi. per. hr. in two minutes. With present average voltage conditions, balancing speed is about 64 mi. per hr. Although comparatively high braking rates have been accomplished on the steam trains, these also have been increased so that electric trains brake at the rate of 1¾ mi. per hr. per sec. It is significant that large decreases have been made in running times even on runs where more stops are made than formerly.

There has been a large gain in electric operation as compared with steam operation from the stand-point of operating a congested terminal. This improvement will become of greater importance as the service grows, inasmuch as under steam operation the limit to the number of trains physically possible to move in or out of the Randolph Street Terminal was rapidly being approached. It is readily apparent that this gain is made by the elimination of movements necessary for steam engines in changing ends of trains, and also in being brought from and taken to the engine terminal, since these movements must be made over the tracks serving useful train movements. The electric train requires only the normal loaded movements over these busy sections, except when brought from or taken to storage tracks at the beginning or end of rush hours.

The speed and reliability of electric service has been further enhanced by other improvements of the entire terminal. These include changes in the grades, rearrangement of tracks, elimination of railroad grade crossings, installation of high platforms at all suburban stations, installment of additional interlocking plants, and rebuilding of the entire automatic block system to conform to electric traction requirements, a great part of which had been completed at the time of beginning electric operation.

### EQUIPMENT

The results obtained from the motor-trailer combination have been satisfactory to the operating officers. The elimination of all steps on the cars for regular operation which requires high platforms, the use of sliding doors, fully enclosed vestibules, tight lock couplers, automatic acceleration, and electropneumatic braking have all tended to increased convenience of the passengers and to safety and speed of operation.

The employment of a large amount of aluminum or aluminum alloys in side and roof sheets, doors, conduit, and fittings has materially reduced the weight of the cars and, thereby, the operating expense.

For the year ending September 1, 1927, the average cost for maintaining the cars has been about six cents per car-mile. The weight of the motor car is 70.65 tons and the trailer 44.27 tons—an average weight per car of 57.46 tons.

Delays due to electrical equipment have been very few and no radical changes in design have been found necessary. Minor changes incident to new designs have been made, but at very slight expense.

Fig. 2 shows the kw-hr. per car mile with corresponding average temperatures. Electric heating of cars is, of course, largely responsible for the variation between the different months, but changes in time-table also affect it slightly.

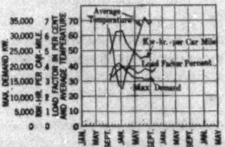


FIG. 2—CURVES SHOWING MONTHLY OPERATING RECORDS WITH ELECTRIC SERVICE (TEMP. IN DEG. FAHR.)

These curves show monthly averages of temperature and kw-hr. per car-mile, monthly load factor, and monthly maximum demand.

### POWER SUPPLY

For the year ending September 1, 1927 the total energy supplied under the contract with the Commonwealth Edison Company was 57,274,512 kw-hr. Of this, 92.7 per cent was for traction purposes including heating of cars, 6.1 per cent for light and power, and 1.2 per cent for signals.

Fig. 2 also shows the maximum demands by months and the variation with the temperature.

The contract provided that the railroad company guarantee a 30 per cent load factor. Fig. 2 shows the variation in the load factor. It will be noted that it is well above the guarantee.

Fig. 3 shows typical summer and winter week day load curves.

The supply of energy by the power company in specified feeders to the right-of-way line of the railroad company from the seven substations has been looked upon from some quarters with misgivings. This requires that not only the conversion machinery but all protective apparatus in the railroad company's feeders be maintained by the power company. The railroad company, however, has taken over, under normal operation, the control of all traction feeders by use of its supervisory control system.

So far the results obtained have been satisfactory with the power company's broad-minded policy in operating under the necessarily somewhat complicated agreement.

Discrimination of the high-speed circuit breakers has been excellent. The overhead network on a multiple track railroad such as this installation covers is complex due to a necessity, in case of a fault, of having a minimum amount of track out of service. Isolation of individual sections in case of trouble has come up to expectations with very good protection to line and equipment. Furthermore, the power supervisor controlling the traction feeders has immediate information as to opening of breakers. He is located in the office of the train dispatcher, so that by working close together, trouble from a train going from a live to a grounded dead section has been minimized. The use of wayside signals indicating a dead trolley section at points where the sectioning is outside the limits of interlocking plants has also saved burn-outs of overhead.

The cold weather of the first winter indicated that a few minor changes, especially in pull-offs, were desirable. The delays which have occurred, however, have been small considering the size of the installation and the number of trains operated.

### GENERAL RESULTS

As indicated on Fig. 1, it is apparent that the traveling public will use a clean, fast, and reliable transportation system. The off-peak business has increased materially, which, of course, is the most satisfactory business to have.

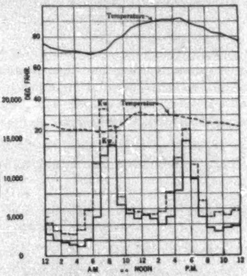


FIG. 3—TYPICAL SUMMER AND WINTER WEEK-DAY LOAD CURVES AND TEMPERATURES

Full lines are for typical summer day, July 27, 1927 (time table No. 5). Dotted lines are for typical winter week-day curve, January 25, 1927 (time table No. 4).

As announced in the newspapers recently, the operating income is now on the right side with an indicated profit of about $530,000 for the year 1927 as against a loss for the year 1926 although the electric service was in operation four complete months during that year. It is pointed out, however, that these figures do not take into account any investment in road and equipment. In providing the electrified service the railroad spent ten and one-half millions of dollars for new equipment, about four millions for electrical work, including overhead, switching equipment, return system and miscellaneous, and about nine and a half millions for rearrangement of old tracks, new track and station facilities and separation of grades, or a total of twenty-four millions in improvements only. An additional twenty millions of dollars was spent in the rearrangement of the terminal facilities for the whole electrification project.

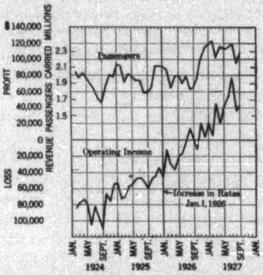


FIG. 4—CURVES SHOWING, MONTHLY NET OPERATING INCOME AND NUMBER OF PASSENGERS CARRIED PER MONTH

Figures for Illinois Central suburban service including Chicago, South Shore, and South Bend Railroads

Fig. 4 shows the relation between operating income and passengers carried for the three and one-half years.

## Discussion

**A. M. Garrett:** I want to mention the operation of the high-speed breakers which are installed upon the feeders.

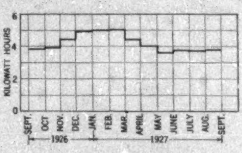
For a short time after the electric railway system was placed in service, we experienced as many as 400 to 500 openings per month of the feeder breakers in a substation. During this period none of the breakers in any of the substations failed to operate properly, which shows exceptionally good performance.

**A. J. Klatte:** The achievement that the Illinois Central has made in turning a loss to a profit is the most outstanding feature of the entire year's efforts.

A remarkable feature of the whole thing is the frankness of the details of the contract between the Illinois Central and the power distributing company here in Chicago. The statement that the power company met all of the Illinois Central's difficulties of operation and cooperated fully, is heartily endorsed by the experience we have had here in Chicago.

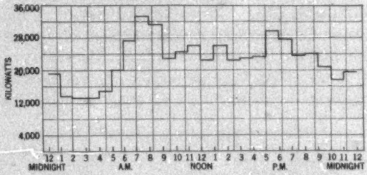
To my surprise instead of losing revenue as a result of this electrification, the Chicago surface lines have had an increase in the number of revenue passengers on every line adjacent to or crossing the Illinois Central.

**Sidney Withington:** (communicated after adjournment) The figures indicating approximately 4.6 to 6.4 kw-hr. per car-mile are among those which are of especial interest. It is understood, however, that they represent power measured at the substations, and therefore include distribution losses. It would be of interest to have the power consumption measured at the pantograph. The seasonal variation is of course a function of journal friction as well as of car heating. The power consumption figures on the New Haven are presented herewith by months, and run from approximately 4.0 to 5.7 kw-hr. per car-mile measured at the pantograph on the a-c. zone. Adding, however, transmission and distribution losses, these figures would be about 4.2 to 6.0 respectively. It is of course true that the power consumption is a function of frequency of stops, rate of acceleration, as well as weight of cars, grades, etc., and no comparison should be made without taking these conditions into consideration.



K. W. H. Per Car Mile.

The power curves which Mr. Vandersluis presents indicate clearly the advantages which would accrue if electrification included yard switching and freight and through-passenger operation in addition to suburban service. The valleys during the middle of the day and at night would be largely filled up, and the load factor correspondingly improved. A typical daily load curve for winter and summer on the "New Haven" is presented herewith as a comparison. The load factor improvements, of course, would apply not only to power supply but also to substations and distribution facilities, and these improvements obviously would make an important difference in the capital or overhead and other fixed charges.

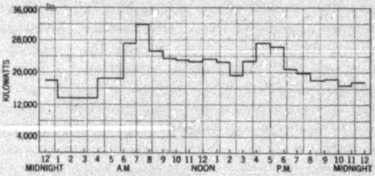


Load Curve for a Typical Winter Day

The cost of maintenance per car-mile of 6 cents may be compared with a cost on the New Haven of approximately 4.5 cents, which includes complication caused by dual a-c./d-c. apparatus, a feature of New Haven equipment on account of operation over the third rail of the New York Central tracks. It is possible that the Illinois Central figures include items not included in the New Haven figures. It seems probable that the first year of operation would provide somewhat less maintenance costs than subsequent operation as the cars grow older and more replacements are required on account of wear. On the other hand, there may be some extra expense during the first year's operation on account of a new organization or in correcting minor defects.

A comparison of ratio of weight and nominal hp. of the motor cars and trailers is of interest. The normal two-car operation of the Illinois Central with 71 tons on the motor car and 44 on the trailer gives a total of 114 tons per pair of cars. This, correlated with the nominal horse power of the four motors at 250 hp. (it is presumed this is continuous rating) gives a figure of .114 tons per hp. The New Haven multiple-unit cars operated nominally with one motor car at 88 tons to two trailers at 52 tons each, comprise a combined weight for the three cars of 192 tons. The nominal continuous rated capacity of New Haven motors is 150 hp., and the aggregate motor capacity for each three cars is therefore 600 hp. The ratio of weight to rated hp. is therefore 0.32, or about three times that on the Illinois Central. It is true that on account of make-up of trains it is not possible on the New Haven always to operate on a ratio of one motor car to two trailers, but the actual operation is not far from this figure.

The above comparison, of course, does not by any means necessarily represent actual load conditions on the motors, as the load depends on the frequency of stops, rate of acceleration (relatively high on the Illinois Central), speed, grades, and many other factors which can be considered only in a lengthy analysis.

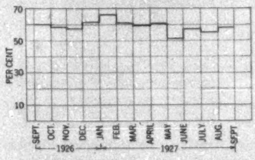


Load Curve for a Typical Summer Day

The figure of $4,000,000 for electrical work, including overhead, switching equipment, bonding, etc., but presumably not including substations, seems somewhat high, but it is understood to include a number of facilities which are designed for the ultimate electrification and a number of items not directly chargeable to electrification, such as signal and station lighting facilities, and it is thus hardly fair to consider it as a figure for "electrification" or to assume the fixed charges as a burden on the electrification.

It is emphasized that the returns on any given electrification project are largely dependent upon the "factor of use" or load factor of each item, not only of power supply, but of transmission facilities, substations, distribution system, etc.; and the full benefit cannot usually be realized until all classes of service on a given project are electrically operated. When this occurs on the Illinois Central, it seems entirely likely that the returns will more than pay the fixed charges on the installation.

It is hoped that Mr. Vandersluis' presentation will stimulate other railroads to present operating figures for comparison, although it must be constantly kept in mind that a great deal of careful analysis is necessary in utilizing such figures to insure that they are on a strictly comparable basis.



System Load Factor

**W. M. Vandersluis:** In connection with Mr. Klatte's remarks, I wish to emphasize the fact that while the operating revenue has increased, yet the Illinois Central is a long way from making any money on account of the electrification of its suburban service. The operating accounts do not include any interest on the investment.

Mr. Withington compares the tons per hp. of the New Haven equipment with the Illinois Central, using the 250-hp. nominal rating of the motors as the continuous rating. The figure of 250-hp. per motor is the one-hour rating. The ratio of weight to rated hp. is 0.1675 instead of 0.1140 mentioned by Mr. Withington.

# 120-Ton Storage-Battery Locomotive
## Performance in Chicago Terminal Freight Yards

BY EDWARD TAYLOR[1]

**Synopsis.**—*This paper describes the design and performance of a 120-ton storage-battery-driven locomotive which has been in switching service in the freight yards of the Chicago railroad terminals. It shows that this locomotive has many advantages for this service including absence of smoke, quietness, a high factor of availability, ease of control, and economy.*

---

RAILWAY yard switching in metropolitan areas involves problems and limitations not met with in less densely settled districts. In Chicago it has seemed desirable to lessen the smoke produced in these yards and electrification of the tracks in the yards has been suggested as a remedy. Complete electrification however presents many difficulties, both physical and economic.

After considerable study it appeared that a combination system of electrification of some of the tracks and use of storage-battery-operated locomotives would go far to solve this problem. It was therefore decided to design and construct a storage-battery yard-switching locomotive and to test it under operating conditions in order to determine its practical and economic possibilities.

This locomotive has now been in service over a year in several switching yards in Chicago. Its performance records, which are reported in this paper, show that it has many advantages. A summary of the results of the tests is as follows:

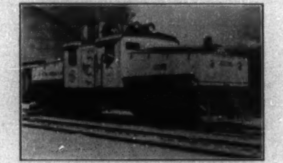


Fig. 1—Storage-Battery Locomotive

I. With one charge (616 kw-hr. capacity) it will do the following:

(a) Make 340 runs of 0.119 mi. including acceleration, with a trailing load of 306 tons, (5 61-ton cars) at an average speed of 5.4 mi. per hr. over a period of 12.5 hr., which allows 60 per cent for actual running time. See Fig. 7.

(b) Haul a 306-ton trailing train (5 61-ton cars) ½ mi. including acceleration, and make 101 such moves at a balanced speed of 17 mi. per hr.

(c) Haul a 500-ton train (8 62½-ton cars) at 16 mi. per hr., taking 6 lb. per ton for traction, at an hourly output from the battery of 147 kw-hr., and will continue to haul it for 4.2 hr.; or it will haul the 500-ton trailing train for 67 mi., or 33,500 trailing ton-miles.

(d) It can do 12 hr. of the average yard-switching service of all the railroads in Chicago on one charge and can be recharged in six hours. This locomotive is equipped with a socket for charging from central station off-peak power at relatively cheap rates.

II. It can exert a tractive effort of 60,000 lb. at 3 mi. per hr. It is controlled handily and smoothly, has a high factor of availability, requiring a minimum of time for getting ready, and a minimum of attention when not operating.

III. It can readily be equipped with a 25- or 60-cycle motor coupled to the present generator, and in connection with a pantograph, collect its replacing charge if desired from a simple trolley carried over a convenient track and thereby be available for service 24 hr. a day.

IV. It operates quietly, without smoke, noxious gases, or steam and is a handy tool for the work of terminal switching and sounds a new note in motive power for congested terminals.

V. Its operation is more economical than steam and it may be a preliminary step to a progressive electrification if desired.

Yard-switching data which could be used in designing the locomotive were somewhat meager and conflicting as would be expected from the radical differences in operating conditions in the various yards. The following, however, represent average typical switching conditions with steam locomotives in the Chicago yards. These data are given in the Smoke Abatement Report of the City of Chicago.

| | |
|---|---|
| Average weight train incl. locomotives | 425 tons |
| " length all switching moves | 628 ft. |
| " distance traveled by locomotive in one 8-hr. shift | 26 mi. |
| " speed while in motion | 5.4 mi. per hr. |
| " ton-mi. for steam locomotive on usual two 8-hr. shifts per day | 22,000 ton-mi. |
| Proportion of time in motion while assigned | 60% |
| Coal consumed per hr | 0.37 tons |

After considering all available data a locomotive was built with the following specifications:

---

[1] General Electric Co., Chicago, Ill.

*Presented at Regional Meeting of District No. 5 of the A. I. E. E., Chicago, Ill., Nov. 28-30, 1927.*

GENERAL DESCRIPTION STORAGE-BATTERY LOCOMOTIVE NO. 10036

*Dimensions:*

| | Ft. | In. |
|---|---|---|
| Total height | 14 | 6½ |
| Width over rain guard | 10 | 3 |
| Width over grab handles | 10 | 7⅝ |
| Length over sill | 49 | 0½ |
| Truck centers | 31 | 0 |
| Length over face of couplers | 52 | 0 |
| Rigid wheel base | 8 | 0 |

*Weight:*

| | |
|---|---|
| Locomotive complete | 237,000 lb. |
| Storage Battery | 78,960 lb. |

*Performance:*

| | |
|---|---|
| Tractive effort 6 mi. per hr. | 39,200 lb. |
| " " 12 " " " | 14,700 lb. |
| Locomotive horse power | 800 hp. |
| Maximum tractive effort at 30% coefficient of adhesion | 71,000 lb. |
| Maximum speed, light | 30 mi. per hr. |

*Equipment:*

4 GE-287 motors, 200 hp. at 300 volts each, with forced ventilation, gear reduction 66/16; 39 in. wheels.

1 Winton gas engine, Model 106-A-220 hp. 1000 rev. per min., 6-cylinder, 7¼ by 8 in. cylinders, direct-connected to DT-509-A 135-kw. shunt-wound 230-volt generator. Radiator for engine is blown. Capacity of gas tank 150 gal.

1 Storage battery "Exide Ironclad"—120 cells FL-31, 2700 ampere-hr. capacity at 230 volts, or 616 kw-hr.

1 PCL control—20 points, including tap field.

1 CP-26, 100-cu. ft. compressor. Straight and automatic air brakes.

ARA draft gear with 5 by 7-in. shank.

The battery chosen for this locomotive is of a type developed for submarine service where the highest quality is essential. This type was selected after an extended investigation had proved that this type was best suited for the kind of operation for which this locomotive was designed. A battery with low internal resistance is desirable, permitting high discharge with low drop in voltage, because a locomotive of this type is inherently a heavy-duty low-load-factor machine.

The characteristics of the battery, motors, charging generator, and entire locomotive are given in Figs. 2 to 7.

The battery consists of 120 cells having a tota weight of 40 tons. This weight is placed half on each of the two locomotive trucks, and as as every locomotive wheel is a driver it might be said that the locomotive tender has been placed on the drivers. In contrasting this tender with that of a steam locomotive, a very great difference is evident, for whereas the coal for the steam locomotive must be fired to generate steam for the cylinders, the power from the electric tender is available to the traction motors instantly and in such quantities as is required by the work. The normal battery rating is 450 amperes for 6 hr. Due to the high-discharge-rate characteristics of this battery a current of 28 times this amount can be drawn from the battery for short periods. The weight of batteries on drivers, giving greater than normal track adhesion, can be utilized thus for occasionally doing work which would be beyond the normal rating of this locomotive.

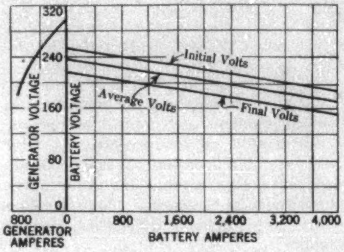


FIG. 2—CHARACTERISTIC CURVES OF STORAGE BATTERY AND GENERATOR

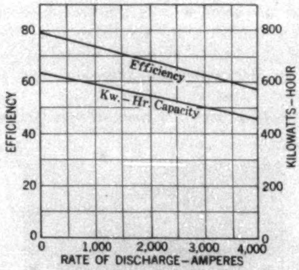


FIG. 3—APPROXIMATE EFFICIENCY OF BATTERY AND KW-HR. CAPACITY AT VARIOUS RATES OF DISCHARGE

The efficiency is at the battery terminals and is the ratio of kw-hr. output to kw-hr. input. It is based on: (a) charging the battery in approximately 6 hr., (b) discharging intermittently so that its full ampere-hr. capacity is utilized

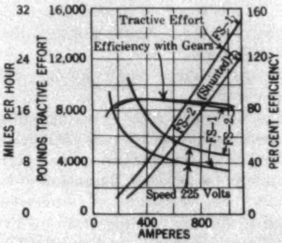


FIG. 4—CHARACTERISTIC OF MOTOR USED ON LOCOMOTIVE

Operated at 225 volts. Gear, 66 teeth. Pionion, 16 teeth. Wheel diameter 39 in.

A storage battery may be considered a potential source of power containing a very definite amount of energy, in this case 616 kw-hr. or 821 hp-hr. This power is available for use at any instant, at any rate from 100 amperes which could be used continuously for 27 hr., to 6000 amperes for short-time operation. In order to get the best service from a battery locomotive its characteristics should be taken advantage of; that is, its assignments should be of such a nature that the average work to be done, including all heavy drags and all stops, allows the batteries to hold up for a reasonable length of time. For instance with the present battery on a 16-hr. job the average rate of work should not exceed 38 kw-hr. per hour, and on an 8-hr. job should not exceed 77 kw-hr. per hour unless means are provided for recharging the batteries while working.

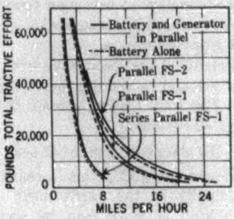


Fig. 5—Tractive Effort Developed by Storage-Battery Locomotive

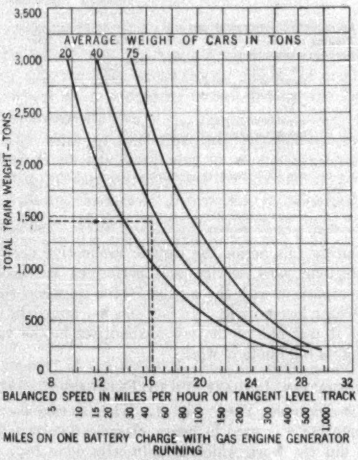


Fig. 6—Performance of Storage Battery Locomotive on Continuous Freight-Train Runs

Train resistance assumed to be as shown in Bulletin No. 43 of the University of Illinois Experimental Station (Professor Schmidt). Locomotive operating in full parallel position with shunted field and with gas-engine generator in parallel with battery

As between batteries of the same construction the life of each depends primarily upon time and temperature. That is, a battery which is used within its discharge rating and thereby is not allowed to attain too high a temperature, will have a much longer life than one which is habitually overloaded. The battery on this locomotive is large enough for the other equipment so that in the service for which the locomotive was designed it is operated well within its rating. Therefore, it is expected to give more than the four years service nominally considered its life.

Each of the 120 cells in this battery consists of a rubber jar containing the plates and electrolyte. Each jar rests in a wooden tray as high as the cell itself and provided with crane eyes for hoisting the cell from its main compartment in the locomotive. Each jar is insulated from each adjacent one and from the compartment floor with porcelain insulators. To replace a cell it is necessary only to unbolt the copper connection straps and raise the cell.

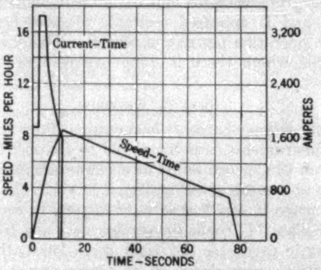


Fig. 7—Characteristic Curves of Average Run in Yard-Swithcing Service in Chicago Terminals

These curves correspond to the average run as shown in Table I.

The 120-ton storage battery will haul this average trailing load the same distance with the same average running speed as the steam locomotive, and, providing its running time is 60 per cent of the total time, will continue to do this service for 12.5 hr. on one battery discharge, without use of auxiliary gas engine, making a total of 340 runs.

To do this requires that each run be of the character shown by the speed-time curve above. The initial rate of acceleration is 1.0 mi. per hr. per sec., corresponding to 19 per cent adhesion and 860 amperes per motor during the period of notching up the controller. Power is shut off at 8.4 mi. per hr. and the train coasts down to 3.3 mi. per hr., with a retardation rate of 0.08 mi. per hr. per sec., after which the train is braked to a stop at the rate of 0.87 mi. per hr. per sec. . Total time of run 79.3 sec., distance covered 0.119 mi., average speed 5.4 mi. per hr., trailing load 306 tons, total load 426 tons.

It is anticipated that under service conditions less coasting and a lower initial rate of acceleration will be desirable, giving the same average running speed. This will require more power for each typical run and the time of operation for one battery discharge may be brought down to 8 hr., with a total of 218 runs.

About once a month replenishing water is needed to compensate for evaporation. Ordinary hydrant water is used for this purpose. This filling and an occasional overcharge to equalize the condition of the cells are all the attention which the battery requires. This is the extent of work done on the locomotive storage batteries during eight months of switching service on six Chicago railroads.

Operators are at times reluctant to use a storage battery for heavy haulage work as many features of its operation and costs are not fully understood. Steam railroads, however, should not be deterred from applying it as they are large users of batteries for car lighting, signal, and other purposes.

Different railroad terminals will have local limitations, restricting their choice of motive power over a wide range; for instance, the yards operated in these tests varied over 20 to 120 kw-hr. per hr. and length of duty from one 8-hr. shift to two 8-hr. shifts as necessary, and it appeared desirable to have continuous 24-hr. operation per day in service. This last is only possible where there is some overhead or third-rail contact.

### SERVICE RECORDS

This storage-battery locomotive, fully equipped with instruments, was completed on October 26, 1926, and run to Chicago on its own power hauling a 60-ton coach at a mean speed of 32 mi. per hr. On arriving in Chicago it was turned over in turn to each of six of the class "I" roads for service tests and trials, displacing in each case the usual steam locomotive. No restrictions were placed on its service except to point out that it was a switcher rather than a road locomotive.

On account of the various types of locomotives used and the methods of operating the locomotives, it seemed advisable to investigate several systems so that a fair mean duty could be arrived at, and the following tabulations are the results of service operation under the wide variety of conditions that exist in the different yards.

### OPERATION IN WOOD STREET YARDS

While this locomotive was in service in October and November 1926 in the Wood Street yards, it was assigned to the various jobs ordinarily performed by 90- and 120-ton (weight on drivers) steam locomotives.

| Kind of work | No. of days, total | Kw.hr. used by loco., total | Assigned wkg. hours, total | Miles of oper. total | Av. kw. used by loco. during wkg. hrs. incl. all stops | | Av. mi. per hr. during wkg. hrs. incl. all stops | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Av. per day | Av. for hardest day | Av. per day | Av. for hardest day |
| Heavy switching | 3 | 1660 | 20 | 62 | 119 | 151 | 3.1 | 3.7 |
| Pulling freight | 4 | 2080 | 24.5 | 115 | 122 | 181 | 4.7 | 5.8 |
| Roustabout | 7 | 3280 | 58.5 | 207 | 81 | 104 | 3.5 | 3.3 |
| Booster | 1 | 450 | 7 | 26 | 92 | 92 | 3.7 | 3.7 |
| Break up | 4 | 2460 | 34.5 | 127 | 102 | 125 | 3.7 | 4.2 |
| Pass. terminal (days) | 4 | 1775 | 34 | 188 | 75 | 91 | 5.5 | 7.4 |
| Pass. terminal (nights) | 3 | 728 | 24 | 78 | 43 | 49 | 3.2 | 2.5 |

The preceding tabulation is a summary which is of interest in showing the actual power required for these jobs.

During the four days of passenger-terminal work the records showed a power consumption averaging 70.6 watt-hr. per gross ton-mi.

The movements of the locomotive from the battery-charging station and return are included in the above tabulation. The total trailing ton-mi. handled during the four days was 16,863.

### IN JACKSON STREET YARD

During December 1926, this locomotive was in service principally in the yards north of Congress Street. The kind of work may be classified under two headings as shown with the length of time in each service.

Freight switching (8 days of 16 hr. each)

Baggage switching in the passenger terminal yards (2 days of 16 hr. each)

Operating data is as follows:

| | Freight Switching | Baggage Switching |
|---|---|---|
| Locomotive-mi. per 16-hr. day | 38.2 | 33.0 |
| Trailing ton-mi. " " " | 13960 | 5000 |
| Average trailing load | 360 | 151 |
| " gross load | 480 | 271 |
| " length of movement (ft.) | 517 | 356 |
| " speed while in motion (mi. per hr.) | 6.7 | 4.7 |
| " speed including all stops | 2.4 | 2.1 |
| " speed including all stops on hardest day | 2.9 | 2.0 |
| Per cent standing time | 64.5 | 56.5 |
| Kw-hr. used by locomotive per 16-hr. day | 1140 | [illegible] |
| Average kw | 71.5 | 49.0 |
| " kw. on hardest day | 85.6 | 49.8 |
| Watt-hr. per gross ton-mile | 61.5 | 86.5 |

During this period the electric locomotive operated in regular yard service and performed successfully in comparison with the regular 70-ton six-wheel steam switching locomotives. In fact on some unusually cold days it was one of the few locomotives in the yards doing its full quota of work.

### OPERATION JANUARY 19 TO FEBRUARY 2, 1927

*Classification Yard No. 1.* The storage-battery locomotive was used in heavy classification switching and did the work which is ordinarily done by a 95-ton (on drivers) steam locomotive.

*Coach Yard.* The work consisted of hauling main-line passenger trains to and from a "Y" point for turning, and miscellaneous switching in a passenger-coach yard. The steam locomotive ordinarily used in this work weighs 64 tons on drivers.

*Union Depot.* This work consisted of switching express and mail cars in and about the main passenger terminal. The battery locomotive in this service replaced a 64-ton (on drivers) steam locomotive.

*Kinzie Street Yard.* Industrial switching. The 64-

ton-on-drivers steam locomotive is ordinarily used in this work.

SUMMARY OF TEST RESULTS
Jan. 19 to Feb. 2, 1927

| | Classification Yard No. 1 | Coach Yard | Union Depot | Kinzie Street Yard |
|---|---|---|---|---|
| (a) No. of days under test | 3 | 1 | 4 | 3 |
| (b) Total hr. and min. in service | 23–25 | 7–38 | 28–26 | 22–11 |
| (c) Total mi., light | 17.3 | 16.1 | 33.1 | 20.1 |
| (d) Total mi., loaded | 55.7 | 22.3 | 70.4 | 31.2 |
| (e) Total mileage (*c* + *d*) | 73.0 | 38.4 | 103.5 | 51.3 |
| (f) Mi. per day (*c* + *a*) | 24.3 | 38.4 | 25.9 | 17.1 |
| (g) Ave. mi. per hr. in service | 3.11 | 5.03 | 3.64 | 2.32 |
| (h) Ave. mi. per hr. while in motion | 4.70 | 8.53 | 7.56 | 4.10 |
| (i) Per cent time in motion (100 g/h) | 66.4 | 59.2 | 48.4 | 56.6 |
| (j) Total no. of cars handled | 966 | 56 | 427 | 507 |
| (k) Total gross ton-mi | 33,413 | 20,351 | 28,518 | 13,004 |
| (l) Ton-mi. per day (k/a) | 11,138 | 20,351 | 7,129 | 4,335 |
| (m) Total kw-hr. used | 2,640 | 692 | 1,484 | 1,230 |
| (n) Watt-hr. per gross ton-mile (1000 m/k) | 79.2 | 34 | 52.1 | 94.7 |
| (o) Ave. kw. in service (m/b) | 104 | 91 | 52 | 55 |
| (p) Hr. on one battery charge (616/o) | 5.9 | 6.8 | 11.8 | 11.2 |

## OPERATION IN LASALLE STREET TERMINAL

On March 26, 1927 the storage-battery locomotive took over for three weeks the assignment of one of the six-wheel steam switching locomotives in the LaSalle St. passenger station.

The work of the switching locomotives in this terminal consists of running in after incoming trains, pulling the cars out to relieve the inbound locomotives and placing the cars on other tracks ready for outbound service or spotting them on express or mail tracks. Trains are also split up and rearranged, and cars put on storage tracks. This switching occupies mainline track and must be done without interfering with the 150 scheduled daily train movements.

The storage-battery locomotive handled this work from March 29 to April 1 very satisfactorily. A summary of the averages obtained from a three-day test in this service is as follows:

| | Average per Day |
|---|---|
| Number of moves | 82 |
| Hr. on duty | 7.8 |
| Mileage while working | 25.9 |
| Mileage of locomotive light | 9.1 |
| Number of cars moved | 177 |
| Kw-hr. used | 461 |
| Per cent time standing | 40 |
| Mi. per hr. including all stops | 3.3 |
| Length of average moment in ft | 1670 |
| Total trailing ton-mi | 3014 |
| Average trailing tons | 116 |
| Gross ton-mi. per hr | 785 |
| Average kw | 59 |
| Kw-hr. per locomotive-mi | 17.8 |
| Watthours per gross ton-mi | 75.3 |
| Hr. for complete discharge of battery | 10.4 |

DATA FROM 22 DAYS OF OPERATION INCLUDING THE 3 DAYS ABOVE

| | Average Day | Hardest day |
|---|---|---|
| Hr. on duty | 8.6 | 8.7 |
| Mileage while working | 28 | 31 |
| Kw-hr used | 490 | 600 |
| Mi. per hr. including all stops | 3.3 | 3.6 |
| Ave. kw-hr | 57 | 69 |
| Hr. for complete discharge of battery | 10.8 | 8.9 |

## OPERATION IN KINZIE STREET YARD

On February 15, 1927 a complete record was made of a typical day's work of freight terminal yard switching in the Kinzie Street Yard. The following is a summary of this day's work:

| | |
|---|---|
| Locomotive-mi. from roundhouse to Kinzie St. yard and return | 6.67 |
| Light locomotive-mi. in Kinzie St. Yard | 6.50 |
| Loaded locomotive-mi. in Kinzie St. Yard | 12.73 |
| Total locomotive-mi | 25.90 |
| Total time in Kinzie St. Yard | 9 hr. 57 min. |
| Percentage of this time standing | 54 |
| " " " " in motion | 46 |
| Locomotive ton-mi. while in Kinzie St. Yard | 2327 |
| Trailing ton-mi | 2893 |
| Total ton-mi. in yard | 5220 |
| Battery discharge while in yard, kw-hr | 428 |
| Average kw. in yard | 42.9 |
| Average kw-hr. per locomotive-mi. in yard | 22.2 |
| Average watt-hr. per total ton-mi. in yard | 82.1 |
| Average mi. per hr | 1.94 |
| Average mi. per hr. while in motion | 4.22 |

SUMMARY OF STORAGE-BATTERY AND STEAM LOCOMOTIVE TESTS FOR 6 DAYS IN CORWITH YARD, MAY 1927

| Storage-Battery Locomotive No. 10035 | Average per day |
|---|---|
| Total weight 120 tons | |
| Weight on drivers 120 " | |
| Hr. on duty | 7.4 |
| Number of moves | 278 |
| Total mileage on duty | 26.4 |
| Light locomotive mileage | 7.7 |
| Number of loaded cars moved | 897 |
| Number of empty cars moved | 552 |
| Length of average movement in ft | 512 |
| Mi. per hr. including all stops | 3.5 |
| Total trailing ton-mi | 6027 |
| Average trailing load in tons | 224 |
| Gross ton-mi. per hr | 1241 |
| Kw-hr. used | 584 |
| Average kw | 79 |
| Kw-hr. per locomotive-mi | 22.0 |
| Watt-hr. per gross ton-mi | 64.3 |
| Hr. for complete discharge of battery | 7.9 |

| Steam Locomotive No. 2084 (3-day test) | Average per day |
|---|---|
| Total weight 126 tons | |
| Total weight on drivers. 77 " | |
| Hr. on duty | 7.4 |
| Number of moves | 295 |
| Total mileage on duty | 27.2 |
| Light locomotive mileage | 5.8 |
| Number of loaded cars moved | 1045 |
| Number of empty cars moved | 593 |
| Length of average movement in ft | 485 |
| Mi. per hr. including all stops | 3.6 |
| Total trailing ton-mi | 5190 |
| Average trailing load in tons | 191 |
| Gross ton-mi. per hr | 1160 |
| Lb. of coal used (incl. firing up) | 8300 |
| Gal. of water used | 3730 |
| Lb. of coal per hr | 970 |
| Lb. of coal per locomotive-mi | 268 |
| Lb. of coal per gross ton-mi | .85 |

SUMMARY OF TEST RESULTS
STORAGE BATTERY LOCOMOTIVE
May 25, to June 1, 1927

| | AveragePerDay Bellewood Yards | 48th Ave. Yards | Lincoln St. Yards |
|---|---|---|---|
| Number of movements | 114 | 139 | 84 |
| Hr. in motion | 5.5 | 5.2 | 3.84 |
| Hr. standing | 2.9 | 2.3 | 4.18 |
| Hr. on duty | 8.4 | 7.5 | 8.02 |
| Total locomotive-mi | 37.9 | 32.2 | 24.2 |
| Light locomotive-mi | 4.8 | 9.0 | 9.6 |
| Total number of cars moved | 745 | 979 | 153 |
| Kw-hr. used | 772 | 681 | 338.8 |
| Per cent time standing | 34.5 | 30.7 | 52.1 |
| Mi. per hr. while in motion | 6.9 | 6.2 | 6.3 |
| Mi. per hr. including all stops | 4.5 | 4.3 | 3.0 |
| Total distance traveled in ft | 200,112 | 170,016 | 127,776 |
| Length of average movement in ft | 1,755 | 1,223 | 1,521 |
| Total trailing ton-mi | 11,519 | 7,906 | 2,154 |
| Average trailing tons | 304 | 245 | 89 |
| Locomotive ton-mi | 4,548 | 3,864 | 2,904 |
| Gross ton-mi | 16,067 | 11,770 | 5,058 |
| Gross ton-mi. per hr | 1,924 | 1,570 | 631 |
| Average kw | 91.8 | 90.8 | 42.3 |
| Kw-hr. per locomotive-mi | 20.4 | 21.2 | 14.0 |
| Watt-hr. per gross ton-mi | 49.0 | 57.9 | 67 |
| Hr. for complete discharge of battery | 6.7 | 6.8 | 14.5 |

## CHARACTER OF WORK

Bellewood Yards, 2 days—Transfer and industrial switching

48th Ave. Yards, 2 days—Heavy classification switching

Lincoln St. Yards, 2 days—Passenger-coach switching.

## CONCLUSIONS FROM TESTS

From the results of the operating records it was concluded that the storage-battery locomotive offers many advantages in metropolitan yard switching. It has demonstrated that it compares very favorably with the steam locomotive.

In general within the capacity of its battery charge it performs more promtly than its steam counterpart. The engine operates quietly and without smoke, cinders, noxious gases, or steam. Particularly in cold weather this means better vision and a consequent saving of time and reduction of accidents.

It is controlled more easily. For the same weight on the drivers the electric locomotive can accelerate a given load more rapidly than the steam by virtue of its more continuous torque. This permits working on the average nearer the slipping point of the wheels. In addition the absence of the tender weight permits either the handling of additional useful load or more rapid acceleration with the same load. These time considerations indicate that more work can be done per engine. In emergency it can be used at considerable distance from its regular yard.

It has a very high factor of availability requiring a minimum of time for getting ready and a minimum of attention when not operating. The power from the batteries is available instantly and in such quantities as required by the work. It does not have to be repaired as frequently as the steam locomotive. It can be kept continually working at the yards, thus saving crew time in going to and from the roundhouse and relieving mainline track of some non-revenue traffic. It can be charged at a station installed adjacent to a convenient siding in the yard where it ordinarily works. The necessity for charging of course limits the number of hours per day during which the locomotive can be used.

If advantage is taken of idle time, such as lunch hours or periods when there is no work, the locomotive can be operating about 20 hr. per day as compared with 16 hr. maximum for the steam switcher. In many cases however, the electric locomotive can be worked on electrified tracks during part of the time (the off-peak period). In this case 24-hr. service may be made available by adapting the locomotive to collect energy from the trolley or third rail. The trolley energy may be used to drive a motor which drives the present generator, thus keeping the battery charged even under continuous operation. It has low maintenance costs.

From published records of the Interstate Commerce Commission it is obvious that maintenance costs of an electric locomotive are one-third to one-quarter those of an equivalent steam locomotive. The operating costs should of course include the expense of replacing the storage battery at the end of the operating life of the cells. The number of men in a yard-switching crew is fixed so that comparison need include only the charges for maintenance of the apparatus and the interest in the investment. The necessary auxiliary appurtenances are low in number.

Coal and water are not needed nor are turntables required since the locomotive may be controlled from either end. Roundhouse space is not so necessary as the locomotive may be kept out of doors summer and winter.

For charging the battery, advantage should be taken of the low off-peak rates of central-station electric companies. The possible yearly kw-hr. are very high, making the load desirable to a central station. The instantaneous and 15-min. peaks are high, which makes the load undesirable for small power stations but the large power company will not be troubled by them especially in off-peak periods. These periods aggregate 12 to 16 hr. per day and rates as low as one cent per kw-hr. may be obtained in some instances. At this rate, considering over-all efficiency, the actual power cost of the locomotive drivers will be about 1.09 cents per hp. hr. When the combination trolley and battery locomotive is used perhaps a certain rate should be charged while operating on the trolley and a separate rate for off-peak power metered separately to the battery.

In conclusion, this storage-battery locomotive not only meets smoke-abatement measures and provides a simple effective tool for yard switching which can be installed quickly without extensive preparations, but it lends itself readily to existing electrifications and fits in excellently with future electrifications. If main-line tracks are already electrified, the battery-type locomotive can be equipped with a trolley or pantograph and be charged directly from the existing distribution system while working, and can work 24 hr. per day with few if any additions to the distribution system. On non-electrified systems, when it becomes advisable to put in a straight electric type where the battery locomotive has been working, the latter is relieved for duty in other yards and thus a complete electrification can be built up with the development of the community without the necessity of great expenditure at any one time.

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## Discussion

(TAYLOR)

CHICAGO, ILL., NOVEMBER 30, 1927

**B. J. Arnold:** The question of various types of locomotives for railroad service is very important at the present time. The gas-electric engine or the Diesel-electric engine for switching service is shown to be the most efficient at the present time. For long, swift work the direct-geared engine outstrips the gasoline-electric combination. The steam engine is making an advance in the triple-expansion engines for marine work. The Diesel engine exceeds that efficiency today, yet the steam engine is keeping pace with the progress of other developments.

**H. H. Field:** I should like to know more about the battery voltage and the motor connections.

**Edward Taylor:** The storage battery on the locomotive is conveniently rated at 230 volts. Batteries of this type are usually rated at their 6-hr. discharge rate and the voltage per cell decreases toward the end of the discharge. Also the voltage per cell decreases as the rate of discharge is increased so that it may be said that the discharge voltage per cell depends on the rate of current discharge, the state of charge, the age of the cell, and to a certain extent on temperature.

The 230-volt motors are equipped with control for connecting, first, two motors in pairs for series-parallel operation, then all four in parallel.

Current could be collected at convenient locations from a trolley or third rail and in this case the number of cells used would be selected to conform to the most desirable charging voltage per cell.

# Operation and Performance of Mercury Arc Rectifier on the Chicago, North Shore, and Milwaukee Railroad Company

BY CAESAR ANTONIONO[1]

Associate, A. I. E. E.

***Synopsis.**—Actual operating results and experiences with a mercury arc rectifier feeding a railroad are given in this paper. The rectifier is compared with synchronous converters in regard to efficiency, troubles, maintenance, and other points.*

THE application of the mercury arc rectifier is one of the newest developments in the railway power field and very little is yet known about its possibilities and applications in this country.

Other papers presented before the Institute have covered the technical points and details on the subject, so that I shall attempt to confine myself to the rectifier's performance on railway work in conjunction with automatic operation.

The development of the rectifier in this country is very much in its infancy as regards its commercial application. It appears to be used more extensively in Europe, and the extent to which it will be applied here is limited only by the economical and operating results which can be obtained.

In considering its application to any property we naturally compare it with the synchronous converter and motor-generator set designed to serve the same class of service, with which we are familiar.

The advantages of the mercury arc rectifier over the synchronous converter and motor-generator according to previous papers presented before the Institute are:

1. High efficiency over the whole working range,
2. Very high capacity to absorb momentary loads,
3. Insensibility to short circuits,
4. No synchronizing,
5. Simple operation and minimum attention,
6. Noiseless operation and no vibration,
7. Low maintenance cost,
8. Reliability of service.

This paper discusses each of these points in connection with the experience we have had with the operation of a rectifier on the Chicago, North Shore, and Milwaukee Railroad. The rectifier is rated at 1000 kw., 600 volts direct current and it is located on the section of the road as shown in Fig. 1. This section is fed also by synchronous converters of 1000-kw. and 1500-kw. rating as shown. This rectifier, made by the General Electric Company, is the first 600-volt machine made in this country which has been installed in actual service.

## EFFICIENCY

The efficiency of the rectifier was compared with that of five converter stations by taking measurements on each substation for five months. The results of the records are shown in the accompanying Table I. The efficiency is taken as the d-c. output divided by the a-c. input. The figures include the efficiency of power transformer and converter or rectifier. They do not include the power used for the operation of automatic devices and auxiliaries such as vacuum pump, motor-generator set, heaters in the rectifier station, nor the power used by auxiliaries and a-c. contactors in the converter stations.

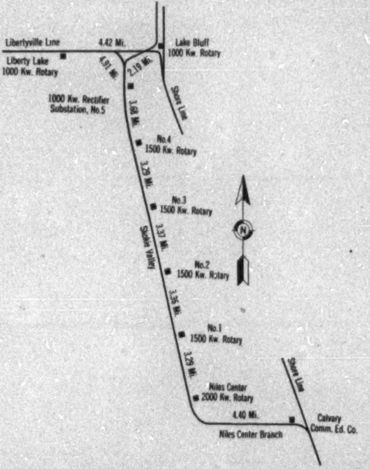

FIG. 1—SECTION OF RAILROAD FED BY RECTIFIER SUBSTATION

Location of synchronous converter substations also shown. Part of Chicago, North Shore & Milwaukee Railroad

I believe this comparison is fair. It was the best method I had of making a comparison in the short time available for preparing this paper. Although not exactly correct, it shows a pronounced difference in the effi-

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[1] Chicago, North Shore, and Milwaukee Railroad Co., Highwood, Ill.

*Presented at the Regional Meeting of District No. 5 of the A. I. E. E., Chicago, Ill., November 28-30, 1927.*

TABLE I

PERFORMANCE OF RECTIFIER AND SYNCHRONOUS CONVERTER SUBSTATIONS

**The kw. and efficiency values do not include the power used for the operation of automatic devices and auxiliaries such as vacuum pump, water pump, motor-generator set, and heaters in the rectifier station nor the power used for auxiliaries and a-c. contactors in the converter stations**

| Substations | | Month of May 1927 | | | | | Month of June 1927 | | | | | Month of July 1927 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total kw-hr. | Total hr. run | Average hr. per day | Average kw-hr. per hour | Per cent efficiency | Total kw-hr. | Total hr. run | Average hr. per day | Average kw-hr. per hour | Per cent efficiency | Total kw-hr. | Total hr. run | Average hr. per day | Average kw-hr. per hour | Per cent efficiency |
| No. 1. substation | A-C. input | 87300 | | | | | 86800 | | | | | 82200 | | | | |
| 1500-kw. syn. converter | D-C. output | 62130 | 341 | 11 | 182 | 71.2 | 59024 | 300 | 10 | 130 | 68 | 57140 | 341 | 11 | 167 | 69.5 |
| No. 2. substation | A-C. | 43500 | | | | | 34200 | | | | | 34200 | | | | |
| 1500-kw. syn. converter | D-C. | 30550 | 201 | 6.5 | 151 | 70.2 | 23214 | 180 | 6 | 128 | 67.8 | 25294 | 201 | 6.5 | 125 | 73.7 |
| No. 3. substation | A-C. | 69600 | | | | | 74400 | | | | | 78300 | | | | |
| 1500-kw. syn. converter | D-C. | 53200 | 310 | 10 | 171 | 76.5 | 58200 | 330 | 11 | 176 | 78.3 | 60800 | 341 | 11 | 178 | 77.6 |
| No. 4. substation | A-C. | 125700 | | | | | 84300 | | | | | 95700 | | | | |
| 1500-kw. syn. converter | D-C. | 97900 | 434 | 14 | 225 | 78 | 62400 | 315 | 10.5 | 197 | 74 | 73000 | 372 | 12 | 196 | 76.3 |
| Liberty Lake | A-C. | 115950 | | | | | 139950 | | | | | 146100 | | | | |
| 1000-kw. syn. converter | D-C. | 83154 | 496 | 16 | 167 | 71.8 | 105844 | 660 | 22 | 160 | 75.6 | 104263 | 715 | 23 | 131 | 71.3 |
| No. 5. substation | A-C. | 89700 | | | | | 75900 | | | | | 79950 | | | | |
| 1000-kw. mercury arc rectifier | D-C. | 71952 | 403 | 13 | 178 | 80 | 62857 | 270 | 9 | 232 | 82.8 | 65747 | 387.5 | 12.5 | 170 | 82.2 |

TABLE I—CONT.

PERFORMANCE OF RECTIFIER AND SYNCHRONOUS CONVERTER SUBSTATIONS

**The kw. and efficiency values do not include the power used for the operation of automatic devices and auxiliaries such as vacuum pump, water pump, motor-generator set, and heaters in the rectifier station nor the power used for auxiliaries and a-c. contactors in the converter stations**

| Substations | | Month of August 1927 | | | | | Month of Sept. 1927 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total kw-hr. | Total hr. run | Average hr. per day | Average kw-hr. per hour | Per cent efficiency | Total kw-hr. | Total hr. run | Average hr. per day | Average kw-hr. per hour | Per cent efficiency | Average effic. of each substation, per cent | Average kw-hr. per hour | Grand average effic., per cent |
| No. 1 substation | A-C. input | 95700 | | | | | 84300 | | | | | | | |
| 1500-kw. syn. converter | D-C. output | 69770 | 403 | 13 | 173 | 72.9 | 61190 | 330 | 11 | 185 | 72.6 | 70.8 | 167.4 | 73.4 |
| No. 2 substation | A-C. | 32100 | | | | | 50220 | | | | | | | |
| 1500-kw. syn. converter | D-C. | 21133 | 186 | 6 | 113 | 65.8 | 33197 | 240 | 8 | 138 | 66.1 | 68.7 | 131 | |
| No. 3 substation | A-C. | 104400 | | | | | 95370 | | | | | | | |
| 1500-kw. syn. converter | D-C. | 83200 | 372 | 12 | 223 | 79.7 | 75300 | 360 | 12 | 209 | 78.9 | 78.2 | 191.5 | |
| No. 4 substation | A-C. | 84600 | | | | | 83040 | | | | | | | |
| 1500-kw. syn. converter | D-C. | 65800 | 310 | 10 | 212 | 77.8 | 62300 | 285 | 9.5 | 218 | 75. | 76.3 | 209.2 | |
| Liberty Lake | A-C. | 119250 | | | | | 118740 | | | | | | | |
| 1000-kw. syn. converter | D-C. | 88246 | 434 | 14 | 203 | 73.1 | 88731 | 525 | 17.5 | 169 | 74.7 | 73.3 | 166 | |
| No. 5 substation | A-C. | 70215 | | | | | 83460 | | | | | | | |
| 1000-kw. mercury arc. rectifier | D-C | 56721 | 341 | 11 | 166 | 80.7 | 67868 | 420 | 14 | 161 | 81.3 | 81.7 | 181.4 | 81.7 |

ciencies of the two types of equipment under nearly similar load conditions and very low load factor.

### Very High Capacity to Absorb Momentary Overload

The ability of the rectifier to carry high momentary overloads is seen from the accompanying Fig. 2 which shows a graphic ammeter chart.

This chart was taken 12 hr. after the unit was put in operation on a day of extremely heavy traffic. It shows load peaks much above the rating of the rectifier. There were no signs of being overloaded, an occasional opening of the high-speed circuit breaker which would reclose immediately, was the only trouble experienced in carrying this load.

Fig. 3 shows the typical load on the station. There are many very high load demands of short duration, some of them well above the rated capacity of the rectifier.

On sustained overload we are not in position to give much information. Usually the load demand above the rectifier rating is of short duration, but there are unusual conditions on the railroad when a load of 175 or 185 per cent of the substation capacity may be carried by any of these stations. The duration of this load is controlled by thermostats on the load-limiting resistors set to release this load in about six or seven min.

It is, however, possible to have a load above the rating of the equipment and below the 175 per cent overload relay setting for a much longer time than 7 min. A load of this kind would be without thermostatic control and might last indefinitely. It could be caused by traffic schedule disarrangement on account of trouble, extra passenger or freight service, or a trolley wire on the ground at such a distance that the resistance of the feeders would limit the current.

Happenings of this nature are not unusual on a railroad and I believe that we have more than one time imposed on the rectifier an overload of much longer duration than we know. There are no recording instruments to show when this occurs. The rectifier does not show any signs of having been abused; momentary opening of the high-speed circuit breakers is the only indication that there must have been excessive load.

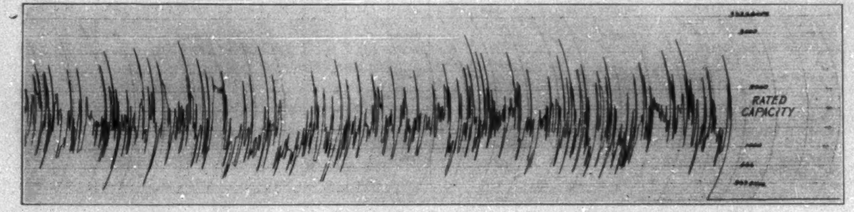


FIG. 2—CURRENT DELIVERED BY MERCURY ARC RECTIFIER ON DAY OF EXTREMELY HEAVY LOAD

Part of record of June 24, 1926 on Substation No. 5 of Chicago, North Shore, and Milwaukee Railroad

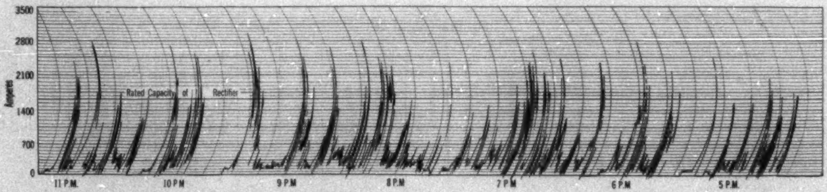


FIG. 3—TYPICAL LOAD ON THE RECTIFIER SUBSTATION

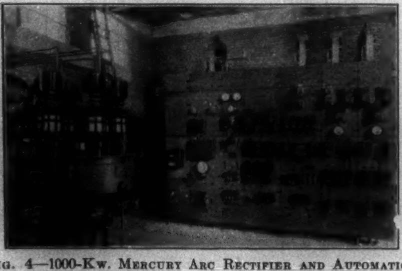


FIG. 4—1000-KW. MERCURY ARC RECTIFIER AND AUTOMATIC SWITCHBOARD

Substation of Chicago, North Shore, & Milwaukee Railroad

### INSENSITIVITY TO SHORT CIRCUITS

Our experience shows that the rectifier is not sensitive to short circuit. Repeated reclosing on a short circuit does not affect the rectifier. Under the same treatment a synchronous converter of the same capacity would be likely to flashover regardless of the protective devices, and in an automatic substation it would lock itself out and the station would be shut down until an inspector could put it back in service.

### NO SYNCHRONIZING

The fact that synchronizing is not necessary with the rectifier is quite important. In the automatic stations on our system only 4 to 6 sec. are required to connect a rectifier to the line. From 20 to 35 sec. are required to put a converter on the line. Therefore we can deliver a higher voltage to the train and trolley 16 to 29 sec. sooner with a rectifier.

### SIMPLE OPERATION AND MINIMUM ATTENTION

We must agree that the mercury arc rectifier requires less attention than the synchronous converter, and its operation is much simpler. There are no brushes, commutator, nor slip-rings to take care of. There is no dust spreading over the equipment. These advantages are very much appreciated in automatic stations without attendance. The ventilation of the equipment and building is also simplified as compared with converters, especially in unattended stations.

I do not want to create the impression that there are less devices involved in the mercury arc rectifier than there are in the converter station. On the contrary, with the rectifier more auxiliaries are used, such as arc-starting exciters, vacuum pump, water supply, temperature regulators, tank heaters, etc. While in our case some of these devices have caused a large number of shut-downs, the troubles were in the individual pieces of apparatus and they have been corrected. Those devices should not need much attention.

### Noiseless Operation and No Vibration

The absence of vibration and noise in the mercury arc equipment makes it possible to install it in locations where the synchronous converter would not be allowed. In one converter installation it cost about $8000 for sound-proofing and ventilating the substation building, eliminating the noise to comply with the wishes of the surrounding residents. Such expense would not have been necessary with mercury arc equipment. Incidentally in addition to the first cost we have added ventilating equipment and extra building maintenance. Obviously, with the absence of vibration it is not necessary to install special foundations for the rectifier. It may be set on an ordinary floor. Ventilation becomes of minor or no importance, and in general a less expensive building is required.

### Lower Maintenance Cost

We do not know at this time just what maintenance will be necessary on the rectifier.

From May 1926 to May 1927 this station was attended by an operator and the manufacturers of the rectifier kept a close watch on its performance. Being in a development or trial stage they took care of necessary maintenance. In addition, new developments which they made in other installations were applicable to this equipment and minor changes were made accordingly. Since May of this year this equipment has been in automatic operation without an operator. The maintenance required is very little; outside of the regular weekly inspections it has amounted only to applying a little oil. Like others we are watching this item with a great deal of interest. Our impression is that the maintenance will be very much less than that required for a converter although some manufacturers may have stretched this point a little too much. Time will tell.

### Reliability of Service

The automatic rectifier station is as reliable, or more reliable, than the average 60-cycle synchronous converter station of the same capacity.

The record for this rectifier substation, commencing May 1926, when it was first started and put in service, all through a trial and adjusting stage until May 1927, when it was made automatic is as follows:

RECORD OF SHUT-DOWNS OF RECTIFIER

| Cause of shut-down | No. | Total time, min. |
|---|---|---|
| High temperature of tanks | 2 | 48 |
| Exciter trouble | 39 | 536 |
| Driving chain and motor on water pump | 13 | 315 |
| Loose connection and bad control circuit | 3 | 50 |
| Vacuum-pump trouble, motor and oil pump | 3 | 260 |
| Flashover of anodes | 6 | 819 |
| Starting anodes sticking | 5 | 602 |
| Misc. unknown | 12 | 1109 |
| Total shut-downs | 83 | 3739 |

Total time rectifier operated 337,140 min.

| Shut-down by failure of | No. of times | Ave. time min. | Per cent of time of operation |
|---|---|---|---|
| Rectifier | 25 | 58 | 0.435 |
| Auxiliaries | 58 | 39 | 0.674 |
| All | 83 | 45 | 1.109 |

Commenting on the foregoing data, it is of interest to note that the time the rectifier was out of service on account of troubles with the rectifier itself was 0.435 per cent of the total time. The time lost on account of the auxiliaries failures was 0.674 per cent of the total time.

The nature of the trouble with the auxiliaries is rather interesting. A larger amount of trouble might be expected with the rectifier on account of its newness in the field, but to have a small motor-generator set or a chain on a water pump and motor cause this bad record is out of place in our days. Engineers have been building and operating motor-generator sets and water pumps for years, but in this case we were after the big things but let the little things cause the most trouble. Fundamentally the record is good, the nature of the troubles is not serious. Since May 1927 the record as an automatic substation is as follows:

| Failure in auxiliary | No. of shut-downs |
|---|---|
| Motor on one vacuum-pump burned out | 1 |
| Locked out after third reclosing of the oil circuit breaker within a definite time during storms | 3 |
| Locked out on account of broken spring on oil-switch mechanical latch | 3 |
| Locked out after third reclosing of the oil circuit breaker within a definite time, cause unknown | 5 |
| Fuse blown on operating transformer supplying power for the operation of devices | 1 |
| Total shut downs | 13 |

Of all these shut-downs, the five lock-outs after the third closure of the oil switch could be questioned and possibly may have been caused by arc-back in the rectifier, or other troubles in the control which we have not detected. All the remaining troubles were not inherent with the rectifier, but were caused by other devices.

Our confidence in its reliability is such that we have established a weekly inspection for this rectifier station, but we do not consider it advisable at present to leave a converter so long without inspection.

The record of the rectifier was compared with that of a synchronous converter of modern design and of the same capacity. This converter is located on another section of the railroad where the load conditions are about the same. It is protected from excessive loads by load-limiting resistors without high-speed circuit breakers. In this comparison I used none of the converters shown in Fig. 1 because these converters are of larger capacity than the rectifier and naturally they are more stable and would take a larger shock and carry more load without flashing over; nor have I used the converter at Liberty Lake, Fig. 1, as the momentary load demands on this station are less than they are on the rectifier.

The converter which I compared had 45,434 hr. of run on its record on May 1927 and had 34 flashovers causing as many shut-downs, representing 276 hr. out of service on account of flashovers. There was an average of 8.1 hr. out of service per shut-down as the majority of these flashovers, damaged commutator flash barriers, brushes, brush rigging, and the insulation in other parts of the machine.

Since May 1927 to date this same converter flashed over 8 times and due to the many flashovers which this machine has had, extensive repairs had to be made on the commutator, rings, and other insulation involving 150 hr. in one shut-down.

This record seems to indicate that the troubles with the rectifier itself probably will not be as serious as with the converter of the same capacity under similar load condition.

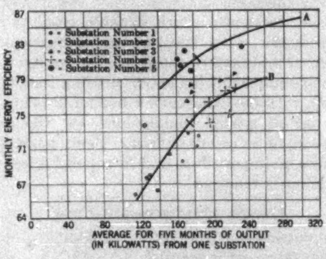
The writer has great confidence that the mercury arc rectifier is here to stay and predicts that 10 or 15 yrs. from now a large application supplementing the converter. The converter had its day, the rectifier's day is coming. It is true that the rectifier at present costs more than the converter of the same capacity and there is some misunderstanding as to its rating. But with an increasing number of installations and our cooperation, as operators, with the manufacturers, the development process will be speeded up and the production cost will naturally be reduced to a figure comparable with that of the converter.

## Discussion

**H. M. Hobart**[1] (communicated after adjournment) It is sometimes said that there is little or no justification for employing the mercury arc rectifier for systems with as low a pressure as 600 volts. While the superiority of the rectifier may, speaking generally, be said to increase with the voltage of the system supplied, Mr. Antoniono's investigations show that it has a notable economic advantage over the synchronous converter even at 600 volts for the kind of service for which it is employed on the Chicago, North Shore, and Milwaukee Railroad.

Analyzing the data given by Mr. Antoniono in Table I, we find that for the five months covered by the records the 1000-kw., 600-volt rectifier substation carried an average load of 181 kw. which is 18.1 per cent of its rated output. For the same period the four 1500-kw. synchronous converters in substations numbered 1, 2, 3, and 4, carried an average load of only 175 kw. which is only 12 per cent of their rated output. (The Liberty Lake 1000-kw. synchronous converter carried an average load of 166 kw. or 16.6 per cent of its rated output, but the author states that on that station the momentary load demands are less than they are on the rectifier substation.) The accompanying illustration contains two curves, *A* and *B*, relating respectively to the observed monthly energy efficiencies of the 1000-kw. rectifier substation and the four 1500-kw. synchronous-converter substations of which the data are given by Mr. Antoniono in Table I. At the rectifier's five months average load of 181 kw. the monthly energy efficiency is seen to be 81.5 per cent as against the synchronous converter's monthly energy efficiency, at the five months average load of 175 kw., of 74 per cent.

Thus the rectifier substation has under these conditions 7.5 per cent higher efficiency than the synchronous-converter substations. Furthermore the 1000-kw. rectifier substation during these five months carried substantially as great an average load (in fact a slightly greater average load) than the average of the four 1500-kw. synchronous-converter substations and it would appear that its cost should be compared *not* with that of a 1000-kw. synchronous-converter substation but with that of a 1500-kw. synchronous-converter substation. However, the sub-stations may have been equipped in anticipation of increasing load and in that case no rigorous conclusions should be drawn.



A study of Curves *A* and *B*, leads one to consider whether such substations could not be designed for higher loads than averages of only, respectively, 18 per cent and 12 per cent of their continuous rating. Considering first the synchronous-converter substation it must be remembered that engineers have had many years of experience in applying them to all sorts of loads. It is necessary to install synchronous converters of sufficient size to ensure that the momentary peak-load demands are well below values liable to occasion flashovers. The graphic chart shown by Mr. Antoniono in Fig. 3 of his paper shows the frequent recurrence of momentary peak loads of 1800 kw. and the installation of synchronous converters with a continuous rating of 1500 kw. may not have been unduly conservative even though it entailed the undesirable feature of an average load of only 12 per cent of the continuous rating, and the correspondingly low monthly energy efficiency. The occasionally occurring days of exceptionally heavy traffic when the graphic chart of Fig. 2 applies, do not enter much into consideration in the case of the synchronous converter since with this kind of service it is principally the frequency of the peaks of load, and not to much extent their magnitude which is increased on days of heavy traffic. We have so little experience with the application of mercury arc rectifiers to this kind of load, that we ought to continue to be conservative in our installations till we have accumulated on several different installations many more data of the kind contained in Mr. Antoniono's paper.

From our present understanding of the rectifier it would appear that the limiting condition will not be with momentary peak loads as in the case of the synchronous converter, but in sustained heavy loads. Consequently *not* the momentary peak loads but sustained heavy loads on the occasional days of heavy traffic are, in the case of rectifiers, liable to constitute the limiting condition which will determine for this kind of service to what extent we can properly increase the percentage which the average load may constitute of the continuous rating. It may be that while the synchronous converter has such limitations for this kind of service that the monthly average load should be limited to a matter of not much over 12 per cent of its continuous rating, the rectifier substation may not need to be so limited. Indeed it is emphasized at several places in Mr. Antoniono's paper that the rectifier substation, for the conditions under which it is operating, is giving a better account of itself than the synchronous-converter substations at the conditions under which they are operating. If further experience bears out this impression, then the efficiency of the rectifier substation may be moved further up on Curve *A* than the efficiency of the synchronous-converter substation can be moved up on Curve *B*.

It thus appears reasonable to assess at some 7 or 8 per cent the amount by which the rectifier substation's efficiency will be higher for a 600-volt load of this character and to compare the initial costs on the correspondingly revised basis. Mr. Antoniono's comments on this conclusion would be much appreciated.

The efficiencies obtained by Mr. Antoniono and set forth in Table I of his paper are, both as regards the synchronous converter and the mercury arc rectifier, several per cent lower for the average loads to which they correspond than the efficiencies which would be obtained for constant loads of these same values. For instance, the efficiency of the 600-volt rectifier and transformer at 18 per cent of rated load should be about 87 per cent while in Table I the efficiency at this load is given as 81.7 per cent. This is partly due to the load characteristics shown in Fig. 3. For the periods when the load is *below* the average, the efficiency is lowered much more than it is raised by load values *above* the average. Will Mr. Antoniono state if he agrees that this is the explanation of the discrepancy? Furthermore, did not the 1000 kw. of equipment in substation No. 5 consist of two 500-kw. rectifiers?

In conclusion it may be of interest to point out that the improvement in the efficiency which is obtained in the case of the rectifier substation when it supplies a greater load is due exclusively to the improvement in the transformer's efficiency, the efficiency of the rectifier itself being nearly constant at all loads. But in the case of the synchronous-converter substations the efficiencies of transformer and converter both improve with increasing load.

**W. B. Anderson:** (communicated after adjournment) Mr. Antoniono's paper includes operating and performance data of value to the many engineers who are carefully observing the development and application of the metal-tank mercury arc rectifier* in this country. The comparative performance data for four rotary-converter stations and the one rectifier station tabulated under Table I are particularly interesting. The comparative values of over-all efficiency clearly indicate the decided advantage of the rectifier over the rotary converter for applications where the average load is small.

In connection with the various advantages of the rectifier, it might be well to consider some of them in further detail. Building-construction costs for rectifier substations should be substantially less than for substations built to house rotating apparatus. As Mr. Antoniono mentions, converter-substation building costs may include items for special ventilation or noise elimination. The matter of foundation, crane, and wall-construction costs should be of considerable importance. A 1000-kw. 600-volt rotary converter weighs approximately 20,000 lb., its heaviest part weighing between 12,000 and 14,000 lb. A rectifier of equivalent capacity will weigh approximately 5000 lb., the heaviest part weighing about half that amount. The foundation for the converter must not only carry four times the weight, but must be adequate to withstand the vibrations of rotating equipment. In most cases, the rectifier will require no special foundation at all. It is common practise to install a crane in the substation suitable for lifting at least the heaviest part of a machine. The rectifier has the advantage in this instance of almost five to one and for the average rectifier installation no crane should be necessary. In addition, wherever there can be a saving in crane service, there will be a corresponding economy in the cost of substation wall construction. The ultimate result should be a considerable saving in building costs for the lighter and static piece of apparatus. The engineers of one railway property have estimated that approximately $5000 can be saved on a $20,000 substation building by the use of rectifiers rather than rotary converters.

The fact that a given rectifier is suitable for operation at any commercial frequency without a change in rating is another interesting feature. This characteristic of the rectifier may result in its preference to the exclusion of rotating apparatus for certain applications. For instance, let us consider the following example. A given property needs more substation capacity immediately and has only 25-cycle power available. Within a space of two years, the 25-cycle power will be replaced by 60-cycle power. At a small added cost, the transformers can be made good for 25 or 60 cycles and the rectifier itself will need no changes. As another possible application, let us consider a property which is supplied from an a-c. system of an odd frequency. Rotary converters of standard frequency would prove unsatisfactory so that it would be necessary to use de-rated motor-generator sets of standard frequency. By using rectifiers no sacrifice in rating is necessary.

The rectifier has another advantage as regards its applications at different voltages. The fundamental basis of rating for a rectifier is current. Representative curves of the voltage rating at different current ratings have already been published. For instance a given design of rectifier with a rating of 1000 kw. at 600 volts will have a higher kw. rating at 1500 volts. A rectifier could be advantageously applied to a 600-volt system which might later be operated at 1500 volts by a change in transformer connections.

Mr. Antoniono refers to the use of a larger number of auxiliaries on a rectifier than on a rotary converter. I believe that a careful check of the major auxiliaries used on a representative installation of each class of equipment, will show the number to be very nearly the same. In this connection a comparison of the number of control devices required for a typical synchronous-converter station and rectifier station respectively might be interesting. In the October issue of the *Electric Journal*, Mr. M. E. Reagan gives the following comparison:

| | No. of Major Switching Devices | No. of Relays Functioning | No. of Protective Relays |
|---|---|---|---|
| Converter...... | 14 | 11 | 13 |
| Rectifier....... | 9 | 10 | 10 |

However, any comparison made now as to the relative number of auxiliaries and control devices used for each apparatus may be misleading. The rotary converter is a highly developed piece of apparatus while the rectifier is in its infancy. The next few years will see many changes in the rectifier, its auxiliaries, and its automatic control equipment.

**F. D. Newbury:** I think the thing we need most to increase the application of rectifiers is a study of the fundamentals involved in rectifier operation. I think I am correct in saying that all rectifiers, as they are built today by anybody, are built purely on empirical information and rules. We know relatively little of the fundamentals on which the rectifier works.

There is no such limit to rating as there is in the converter or any other electromagnetic machine as in flux and current densities. The amount of current a rectifier will give depends largely on local temperatures and characteristics of materials, and ability to exclude gases from the rectifier tank. A study of those fundamentals will undoubtedly lead to very great reductions in the size of rectifiers for a given current rating.

I don't agree entirely that the case chosen is a fair example from the standpoint of the converter, and remember in what I am saying now all of the nice things I have just said about the rectifier.

It is obviously unfair to compare efficiencies on the basis of stations having such low load factors. It is possible, particularly with automatic stations, to have fairly high load factors, and with high load factors above 50 or 60 per cent of rating there will be no such outstanding difference in efficiency in favor of the rectifier as shown in this case.

Again, in the comparison of short circuits, there is any number of large 60-cycle converters that are operating under severe conditions with practically no flashovers. Probably the greatest need for the rapid application of rectifiers is the ability of manufacturers to supply larger units. That is particularly true at 600 volts. Much of the advantage of the rectifier in station cost is lost if a large number of tanks has to be supplied to give the desired unit rating.

**M. S. Oldacre:** There are two characteristics of the rectifier that have not been emphasized that make the rectifier desirable for other applications than these now usual in this country, and these are the absence of noise and ease of cooling.

In the congested districts of the large cities where rotary converters are used for supplying 250-volt distribution systems, the question of noise and cooling is a problem at the present time. The rectifier solves the noise problem at once. The cooling question is practically solved because the amount of water required is a small fraction of that required by a converter installation, where recirculation of the air is required to obtain adequate cooling if space is restricted. The rectifier gives a much simpler layout.

The rectifiers discussed have a capacity in a single bowl of only 500 to 1200 kw. at 600 volts, and it has been pointed out that large enough rectifiers for 250-volt service are not yet available, the requirements being about 15,000 amperes; but with rectifiers available having a nominal rating of 5000 amperes and a two-hour rating of 7500 amperes at 600 volts and in a single bowl, the indications are that the larger rectifiers may soon be available.

Another point is that apparently the rectifier has been developed in this country and its characteristics are well known to the manufacturers or at least well enough so that they are able to build them after the rectifier has been popularized by some other manufacturer, in this case a foreign manufacturer. It does not seem up to the usual pioneer spirit of our American manufacturer to trail along in that fashion.

**Sidney Withington:** (communicated after adjournment) It is quite refreshing to read a paper on the mercury arc rectifier which is written by a user rather than by a manufacturer of this type of apparatus. The enthusiasm of Mr. Antoniono for the rectifier is apparent, and is obviously justified by the performance.

The Connecticut Company a few months ago placed in operation a 6000-kw. substation at Bridgeport, Conn. (the largest installation of mercury arc rectifiers thus far made, and the only instance where an entire city traction load is carried by this type of apparatus), consisting of five single-bowl rectifiers rated at 1200 kw. each. From the impressive manner in which the substation went into service, with little or no time available for test before it was called upon to carry the load commercially, and from subsequent operation, it is obvious that the mercury arc rectifier is here to stay as an integral facility for traction purposes, and that it has numerous and important advantages over the rotary converter.

The rapid development of this type of apparatus places upon electrical engineers, both manufacturers and users, responsibility for standardization, especially of rating, which cannot be ignored. The load characteristics of the rectifier are so different from those of the rotary converter that attempts to rate one in terms of the other are misleading, and it is imperative that the rating of the rectifier be placed upon a sound and logical basis as soon as possible.

**B. G. Jamieson:** I should like to say that Mr. Schuchardt, Electrical Engineer of the Commonwealth Edison Company, went abroad some six or seven years ago and came back and tried his utmost to get the American manufacturers to interest themselves in this problem, and it is very largely due to his efforts that we now have the rectifier in actual operating performance.

There are one or two other points in connection with the rectifier, one suggested particularly by the lack of necessity of synchronizing. As the rectifier becomes a feature of future trunk-line electrification, we shall see the advantage where the supply of energy has to be taken from different systems. We shall not be bothered with energy interchange between the different systems through trolleys.

There are some other points about the rectifier not so favorable at present. For example, there has not been, so far as I know, any substantial accomplishment toward improvement of regulation. When the requirements of the railway companies take the form of very close regulation and a rectifier is involved, it becomes necessary to look beyond the present art.

Another unfavorable feature of design which unnecessarily exaggerates rectifier outage and which should be corrected is, for example, a case of trouble with an anode, the mechanical replacement of which should not take an hour, but which because of incidental circumstances causes the rectifier to be out of service for 100 hr. Certainly any over-all figure which Mr. Antoniono has given has some elements of this character which exaggerate the reported unfavorable performance.

Other features of the rectifier which were regarded some years ago as basic difficulties have been minimized, but there are still some such features as for example, the question of unknown characteristics of the backfire and the reasons therefor.

**A. Herz:** The matter of noise emitted from rotary converter substations is serious. As the railroad load increases the substations must be located closer together making it unavoidable to locate some in comparatively densely populated sections which in many instances are the better class of residential suburbs.

In our company we have carried on experiments to mitigate the noise by closing window openings with two thicknesses of glass and lining the substation doors and walls with non-sound-transmitting and non-reflecting materials, with the result that artificial ventilation with its noisy blowers, etc., had to be resorted to if temperatures of 110 to 125 deg. fahr. in the summer time and inside the converter substations were to be avoided.

Therefore if we can use a rectifier which is inherently noiseless in place of a converter and do the necessary cooling for the former outside of the substation we have certainly made an advance in every way.

This brings up the matter of cooling the rectifiers. We have had serious trouble with the cooling systems of rectifiers, cases of electrolysis and cases of deposition of mineral matter, the former being particularly serious.

I cannot quite comprehend why the manufacturers do not resort to oil as the initial heat-absorbing medium; that is, use oil for cooling the rectifier proper and circulate this oil through a cooling system making use of fans or water. This would avoid troubles from electrolysis within the rectifier as is now the case and would avoid some other difficulties we now have. The quantity of oil necessary would be quite small.

There is one feature that has not been touched upon, I believe, and that is the item of stored energy. A power system with many large rotary converters in operation thereon has certainly considerable energy stored in the momentum of the moving parts of such machines. The stored energy in the rectifier is practically nil. Therefore an accident occurring to the power system is not aggravated nearly as badly by a rectifier load as by a rotary-converter load.

The item of back-fire has already been mentioned by Mr. Jamieson, and I believe improvements are being made in the rectifier to do away with it, but in any event the back-fire in a rectifier is not more serious than a flashover on a rotary converter which I know we still get although not so frequently as during the times before barriers and arc hurdles were installed over the commutators.

**O. K. Marti:** This paper, written by an operating engineer who has had actual experience with equipment of this kind, is a very good contribution to the rectifier art in this country. It is highly desirable that more operating and service data be made available, because the mercury arc rectifier is a device only recently introduced into this country, and although the rectifier is used to a very great extent in Europe, where there are installed more than 1500 cylinders with a total capacity of about 700,000 kw., there are very few operating data available.

I feel that Mr. Antoniono's paper permits a comparison between the performances of rectifiers and rotary converters in a number of points, such as efficiency, overloads, service interruptions, and the like. There is one point, however, on which it is very hard to come to an impartial conclusion, and that is in the matter of interruptions caused by back-fires (in the case of rectifiers) and by flashovers (in the case of rotary converters). Flashovers produce damage to brushes, brush-holders, commutators, and armatures, and very frequently put the machine in such a condition that it cannot render any service for several days. Back-fires, on the other hand, do not cause an interruption of service for more than a few seconds. In making this comparison one has to keep in mind that in an automatic rectifier substation there is less auxiliary equipment than in an automatic rotary converter substation, and that a rectifier is stationary, while a synchronous converter is rotating. This is another fundamental difference which complicates the problem of making a comparison.

I should like to point out particularly some points relating to the table on the fourth page of Mr. Antoniono's paper, which gives a record of the shut-downs of the rectifier in question. You will notice that most of these shut-downs were due to the auxiliaries, and not to the rectifier proper, as might be expected, and this peculiarity is also pointed out in the paper. It can also be seen that the largest single item, 39 interruptions, was due to exciter troubles, and 5 interruptions were due to the starting anode which is used to ignite and put the rectifier into operation. I should be pleased to have Mr. Antoniono tell us the failure of what particular part of the exciter caused these troubles.

In the installation described in this paper, the arc is ignited by direct current supplied by a small motor-generator set. A starting anode is used which, when withdrawn from the mercury cathode, strikes an arc. This interruption of the current frequently induces a high voltage in the starting circuit, which may cause a break-down of the insulation in the generator or a flashover at its commutator. Brown Boveri employed a similar system of ignition and excitation and experienced similar troubles but as the result of extensive investigations they were able to devise an arrangement for using alternating current for these purposes. Although similar voltage surges occur in the a-c. system, it is much easier to insulate a transformer for these surges than a d-c. generator, and no troubles are experienced with the ignition and excitation system now in use. Furthermore, the Brown Boveri rectifiers do not have any anode heaters nor tank heaters.

It might also be interesting to note that the limits in the capacity of power rectifiers, which were at about 1000 kw. at 600 volts, nominal rating, have now been raised, the American Brown Boveri company offering rectifiers for 6000 kw. at 600 volts, nominal rating, at the present time. This shows that rectifiers can be built for capacities as large as and larger than rotary converters. Furthermore, there are no difficulties with rectifiers in connection with the frequency or the voltage. This is an achievement of great importance. It is therefore likely that Mr. Antoniono's prediction that in 10 or 15 years the rectifier will take the place of the rotary converter, will come true even sooner.

This increase in capacity was made possible by a recently made improvement, the basic idea of which dates back several years. Tests carried out on the latest types of large rectifiers for several months at loads greatly in excess of their capacity ratings have demonstrated their reliability, and therefore the future outlook for the mercury arc rectifier is an excellent one.

**Caesar Antoniono:** The conclusion reached by Mr. H. M. Hobart on my paper is in general in accord with my own conclusion.

The size of the substations units shown in Fig. 1 was decided on in anticipation of future increase in load. The rectifier however, was the largest that could be obtained at that time. While it is true that the load is carried by each converter in its respective section, it is also expected to be carried by the rectifier through its own section as shown in Fig. 1. I agree with Mr. Hobart that we should not arrive at any rigorous conclusion on this point at present regarding cost and rating.

I do not consider that the installation of 1500-kw. units in these substations was unduly conservative, due to the fact that all of the synchronous converters shown in Fig. 1 have already flashed over, due to some disturbance or other which has passed by the high-speed circuit breakers into the d-c. feeders.

I agree with Mr. Hobart's deduction, that sustained overloads are perhaps the limiting conditions on the rectifier, and not the value of the momentary loads. I believe we should have further experience on this subject to support or disprove this conclusion.

I believe it in order at this time to call attention to my discussion on the mercury arc rectifier at Kansas City, March 18, 1927,[1] in which reference is made to a case where one tank of the rectifier under discussion was not carrying any load for over a week, unknown to the operator. The writer feels justified in assuming that during this time the working tank was carrying alone the (typical) load on graphic chart Fig. 3 without showing any sign of having been over-loaded. The assessment of 7 or 8 per cent of the amount by which the rectifier substation's efficiency will be higher for a 600-volt load of this character and to compare the initial cost on this correspondingly revised basis, seems to be a logical conclusion from the data given in my paper. However, we should be rather conservative at present and obtain more data before arriving at a conclusion, in order to avoid the possibility of leaving out some important factor.

The discrepancy in efficiency as referred to in Mr. Hobart's discussion is correctly quoted in his explanation of the load characteristics shown on Fig. 3. Two 500-kw. tanks of 6-anodes in 12-phase relation are employed.

It was brought out that the number of devices in the future is going to be less. I agree with that, but in my paper I was speaking of present installation. I am confident that the number of automatic devices for the mercury-arc rectifier is eventually going to be reduced to fewer devices than required for the converter.

Mr. Newbury brought out that the method of comparing the two efficiencies was not fair. I stated in my paper that this method was not exactly correct. But from the point of view of the operator we are concerned with the total efficiency we are getting from the two different types of equipment, and that is what we are getting from this chain of stations under the existing conditions. He brought out the point that a converter could be improved as to load factor and therefore the efficiency would be improved. If that is feasible, yes, but in our case it is not feasible because the load demand on one of these machines perhaps goes much above 150 per cent and is of very short duration. It may last one, two, or three minutes, and perhaps about five or ten minutes an hour, and that accounts for the very low efficiency we are getting out of the stations. The operator is interested in the efficiency he is getting out of his equipment under that condition.

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[1] A. I. E. E. Journal, October 1927, p. 1104.

Rotary flashover was also mentioned. There are a number of rotaries that don't flash over. We have about 22 rotaries, and they are subject to flashover in spite of all the protective devices used either with or without high-speed breakers. Up to this time the rectifier has done well.

Mr. Withington stated that I am enthusiastic about the rectifier. I am. From the experience we have had so far with the rectifier, I am very enthusiastic about it.

Mr. Jamieson brought out the question of changing the anodes or similar maintenance work, and the number of hours before the rectifier can be put back into operation. That is one thing that as I mentioned in my paper we are not able to tell anything about at this time, and we should like to know ourselves what this is going to be. I feel as Mr. Jamieson does, that improvement can be made or will be made to the extent of eliminating some of the present difficulties with the rectifier and that the future rectifier will be superior to the converter in every detail.

I was informed that one manufacturer is using a carbon anode to eliminate trouble with seals.

With regard to the cooling trouble, it was mentioned by Mr. Herz that there have been cases of electrolysis. I believe there are more or less cases of electrolysis, although we have had no experience with bad effects from electrolysis. I feel as Mr. Herz does, that perhaps there are other methods of cooling. I believe perhaps oil would be the solution of electrolysis.

In connection with auxiliary trouble, I mentioned in my paper that we had trouble in d-c. motor generator sets due to poor operation of the exciters, or commutators, which in turn would result in a shut-down in order to correct it.

Another trouble was with the driving chain and motor on the water pumps. This was due to misjudgment of the amount of water necessary for cooling this particular rectifier. Using a high-speed motor to drive a pump would cause driving chain to jump off and result in a shut-down.

A loose connection in the control circuit is one of the troubles typical of automatic control. Then there was trouble in a motor which was changed from a 3-phase induction motor to a single-phase motor.

# Synchronous Motors for Driving Steel Rolling Mills

BY W. T. BERKSHIRE[1] and H. A. WINNE[1]
Associate, A. I. E. E. Associate, A. I. E. E.

***Synopsis.**—It is the purpose of this paper briefly to discuss, from a practical standpoint, the application and design of synchronous motors for steel-mill main-roll drives, in an effort to show what their advantages and disadvantages are; where they should, and where they should not, be used; and what special precautions must be taken in the design of motors for this service.*

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DRIVING main rolls of steel mills is universally recognized as very heavy duty. The loads are high, and are applied and relieved very suddenly. Consider the case of a motor driving a single stand, Fig. 1. Between passes it will run with only 5 per cent to 10 per cent load, due simply to mill friction. As the metal strikes the rolls the load jumps almost instantly to possibly 100 per cent or 150 per cent of normal, and is as suddenly reduced when the metal leaves. This happens several times a minute. If such a drive has been properly selected, several passes on each bloom or billet may require 150 per cent to 175 per cent normal load on the motor. The load is intermittent in character, so that the motor is selected with the idea of permitting some of the passes to come up to these limits, so long as the r. m. s. value of the load is within the normal rating of the motor. If the heavier passes are of not more than three or four seconds duration a flywheel may be utilized to reduce the peak loads on the motor and power system.

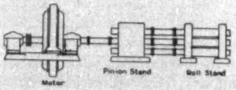

FIG. 1—ROLLING MILL, SINGLE STAND

With a mill having a train of several stands as in Fig. 2 or with a continuous mill as in Fig. 3, the drive is not subjected to quite as severe shocks as with a single stand, for it is apparent that as a piece of metal enters the mill the stands are filled in succession until all are full. The load increases to the maximum value in a number of steps, and is similarly reduced.

The torque required to start a mill from rest is often quite high in comparison to the capacity of the driving motor. This is especially true in cold weather, as very heavy grease is used on the roll necks and pinions, and this becomes very hard at low temperatures. Mills used for cold rolling thin sheets, which operate with very high pressure between the rolls and consequently on the bearings, may require as much as 200 per cent of normal motor torque to break them loose.

In addition to being able to start the mill, and carry heavy and sudden overloads, the drive must usually be capable of withstanding "plugging" in order to bring the mill quickly to a stop in case of a "cobble" or other mishap. Any piece of metal which fails to go through the mill properly is termed a "cobble." As soon as the operator sees that the steel is not going through as it should, he "plugs" the motor by disconnecting it from the line and then applying power with reversed phase rotation. After the mill stops, if the metal is not clear of all the stands, the portions between stands are cut out and then the motor must start the mill in the reverse direction to back out the pieces in the rolls.

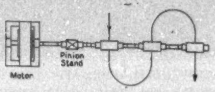

FIG. 2—ROLL TRAIN OF THREE STANDS

Considering these conditions which a main roll drive must meet, it is not remarkable that for nearly all constant-speed electric drives induction motors of the wound-rotor type have been used. This type of motor has excellent starting characteristics, will carry heavy overloads, and withstands much abuse. In common with all induction motors, however, its power factor is lagging, and very much so in low-speed machines. Now, the main rolls and lay-shafts on heavy mills do not run at high speeds, and it is often desirable to direct-connect the motor, so that there are now in service many low-speed motors, operating at low power factors. As a matter of fact, one reason for the use of 25-cycle power in numbers of steel plants is that low-speed 25-cycle motors have better power factor than the corresponding 60-cycle machines. The use of higher speed motors driving through reduction gears

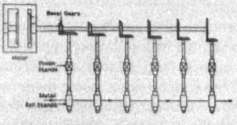

FIG. 3—CONTINUOUS MILL

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1. Both of General Electric Co., Schenectady, N. Y.

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has helped the situation somewhat, but has still left much to be desired in the way of power factor improvement.

Unquestionably the desire for a better operating power factor has been the chief factor in bringing the synchronous motor into consideration in steel mill service. It possesses, however, advantages other than its good power factor, as well as some disadvantages, and these will be brought out in the following detailed comparison of the characteristics of the two types of machines.

FIG. 4—9000-H.P., 107-REV. PER MIN., 6600-VOLT SYNCHRONOUS MOTOR DRIVING A CONTINUOUS SHEET BAR MILL

This motor has a greater continuous horsepower rating than any other motor in industrial service.

## FIELD OF APPLICATION OF SYNCHRONOUS MOTOR

The field of application of the synchronous motor in main-roll service is limited to strictly constant-speed drives. This eliminates it from consideration on reversing mills,—mills requiring flywheels, and mills needing adjustable speed.

It is not as a rule advisable to attempt to apply it to any type of mill which may have to be started with metal in the rolls, such as a cold strip mill, nor to cold sheet mills, which have excessively high friction. Such mills may require at starting considerably more torque than is needed to carry their full load at full speed, and unless the motor is sufficiently small in comparison to the power system so that it can be started at full voltage, difficulty may be experienced in getting started and synchronized.

In connection with constant-speed continuous mills of the type shown in Fig. 3, looping mills as illustrated in Fig. 2, and in fact, almost any constant-speed hot metal mill, the synchronous motor deserves very careful consideration. Every individual case must be studied very thoroughly to make certain that no misapplications are made. Careful thought must be given not only to the full-load rating required, but also to the maximum torque that may be necessary to break the mill from rest under the most adverse conditions; to the maximum torque needed at pull-in; to the torque required to back out cobbles; to the maximum peak load that may be encountered; to the kv-a. demand that the power system can stand without disturbance, while starting the motor; and last, but not least, to the characteristics that can be obtained in the motor, to determine whether it can meet the requirements.

## STARTING CHARACTERISTICS

Practically the only reason synchronous motors have not been widely used on mill drives in the past is because their starting characteristics are not so desirable as those of the wound-rotor induction motor. For 100 per cent kv-a. input the induction motor develops approximately 100 per cent rated torque at starting, whereas the synchronous motor will give from 30 per cent to 60 per cent starting torque with the same kv-a. input at a much lower power factor. However, the torque obtainable from a synchronous motor is ample to start most types of mills, and its other advantages make it the logical choice in many cases.

By proper design, good starting torque characteristics, as shown in Figs. 5 and 6 can be obtained in mill type synchronous motors with a single squirrel-cage winding. The double squirrel-cage has, at times, been considered, but in each case it has been found that by the proper choice and distribution of materials in the bars and rings, the proper spacing of the bars with respect to the stator slot pitch and the depth and width of the slots in the pole face over the bars, the torque requirements have been amply met with a single squirrel-cage. In practically all cases it has been found possible to obtain more than sufficient torque to start and bring the mill to synchronous speed, or to even back out a cobble, with from 70 per cent to 100 per cent normal kv-a. input. Unlike that of the squirrel-cage induction motor the squirrel-cage of the synchronous motor can

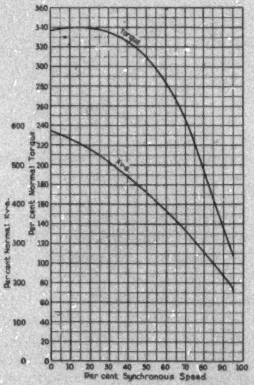

FIG. 5—STARTING CHARACTERISTICS OF 6500-H. P., 0.8-POWER FACTOR, 187-REV. PER MIN., 6600-VOLT, 25-CYCLE SYNCHRONOUS MOTOR, FROM TEST DATA

be changed in design at will, with a corresponding change in torque characteristics, without affecting the efficiency of the synchronous motor during its normal operation under load.

The curves shown give the torque and kv-a. values with full voltage applied to the motor. In normal operation of course, these large motors are started at reduced voltage obtained from a suitable auto-transformer. For example, the 6500-hp., 187-rev. per min. motor for which starting torque and kv-a. curves are shown is regularly started on 32 per cent voltage. Since the starting torque and kv-a. input varies as the square of the voltage, it is apparent that under this condition the motor demands only 60 per cent of normal kv-a. and gives about 35 per cent of its normal torque. This has proved ample to start the mill under all conditions. Similarly, a 9000-hp., 107-rev. per min. motor is always started at 32 per cent voltage, giving 27 per cent of normal torque with 70 per cent normal kv-a.

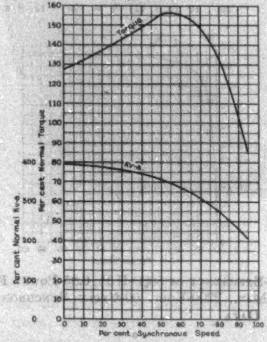

FIG. 6—STARTING CHARACTERISTICS OF 5000-H.P., 0.85-POWER FACTOR, 240-REV. PER MIN., 2200-VOLT, 60-CYCLE SYNCHRONOUS MOTOR, FROM TEST DATA

The "pull-in" torque, or the torque available at approximately 95 per cent synchronous speed before the application of field, must of course be in excess of the mill friction at this speed, but can be considerably less than the starting torque, as the latter must overcome the "dead" friction of the mill, with the bearings practically dry.

The fields of these motors are usually wound for 250-volt excitation, and if the field were left open-circuited at starting the induced voltage across the rings, with 33 per cent normal voltage applied to the stator, would be from 5000 to 10,000 volts. In order to protect the operators from the induced field voltage it is the practise when starting, to close the field circuit through a discharge resistance. While this increases the starting current and decreases the starting torque to some degree, it also increases the pull-in torque. The amount and capacity of this resistance to give the best torque characteristics can be determined by calculation.

A synchronous motor may be plugged for a quick stop, by first opening the "forward" breaker and removing field, then closing the "reverse" breaker and connecting the motor to the starting tap of the auto-transformer. The current drawn when plugging is approximately 15 per cent more than the starting current, and the torque developed about 75 per cent of the torque at starting.

### MAXIMUM TORQUE

A synchronous motor can be designed for fully as high maximum or pull-out torque as an induction motor and for steel mill service this pull-out torque varies from 225 per cent to 300 per cent of normal full load running torque. The synchronous motor has the advantage that for any reduction in applied line voltage the pull-out torque decreases only in direct ratio to the voltage, whereas the torque of an induction motor decreases as the square of the voltage. Furthermore because of its better power factor, the synchronous motor helps to maintain the voltage at its terminals; consequently the drop in line voltage due to a given load is not likely to be so great as if an induction motor were used.

### POWER FACTOR

One of the most desirable features of the synchronous motor is its ability to improve the power factor of the system on which it operates. It is usually designed to give a leading power factor at normal load, and will then furnish a considerable amount of corrective kv-a. at all loads up to a considerable overload, as shown in Fig. 7. The low power factor of low-speed induction motors, particularly 60-cycle machines, has necessitated the use of reduction gears in some cases where for other reasons a direct drive would have been preferable. The use of synchronous motors permits direct drive with low-speed machines, operating at unity or leading power factor.

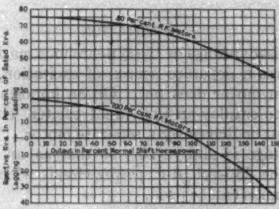

FIG. 7—APPROXIMATE REACTIVE KV-A. AVAILABLE FOR POWER-FACTOR CORRECTION, WITH FIELD EXCITATION CONSTANT AT NORMAL LOAD VALUE

## EFFICIENCY

Two curves are shown, illustrating the very high efficiency obtained from large synchronous motors, both 25 and 60 cycles. The fact that approximately 75 per cent efficiency is obtained at 5 per cent of normal load is quite noteworthy.

The full-load efficiency of synchronous motors for steel mill service varies from 0.5 per cent to 2 per cent more than that of the corresponding induction motors. This better efficiency of course means some saving in power cost.

## OPERATING VOLTAGE

Synchronous machines can very readily be built for any operating voltage up to and including 13,200. While a very few induction motors are operating at 13,200 volts, it is better practise not to exceed 6600 volts on an induction motor, as the design becomes difficult and the machine expensive.

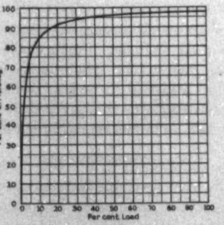

FIG. 8—EFFICIENCY OF 9000-HP., 1.0-POWER FACTOR, 107-REV. PER MIN., 6600-VOLT, 25-CYCLE SYNCHRONOUS MOTOR, FROM TEST DATA

## EXCITATION

One disadvantage of the synchronous machine is that it requires a separate source of excitation, while the induction motor does not. On an important drive it is wise to employ an individual exciter, either direct connected or driven by a separate motor. The excitation voltage is always 250, so that as an emergency source the 250-volt d-c. power circuit which exists in all steel mills can be used.

## FLOOR SPACE

The amount of floor space required by a synchronous motor is almost invariably less than that needed for an induction motor of the same rating. One reason for this is that it is the usual practise to make the motor base long enough so that the stator can be moved along the shaft a sufficient distance to make both rotor and stator windings accessible for cleaning or repairs. The rotor of an induction motor is inherently somewhat longer than that of a synchronous motor, because of the space required for the end connections of the coils on the former, and this necessitates a greater space for movement of the stator.

The following table shows the relative base dimensions of the two types of motors, for several different ratings:

| | | | Floor Space | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rating | | | Synchronous Motor | | | | | | | Induction Motor | | | | | | |
| H. P. | Rev. per min. | Cycles | Ft. | In. | | Ft. | In. | | Sq. ft. | Ft. | In. | | Ft. | In. | | Sq. ft. |
| 9000 | 107 | 25 | 18 | 0 | x | 24 | 8 | = | 445 | 20 | 7 | x | 25 | 0 | = | 515 |
| 6500 | 187 | 25 | 17 | 5 | x | 15 | 7 | = | 272 | 16 | 7 | x | 19 | 3 | = | 319 |
| 5000 | 100 | 60 | 13 | 2 | x | 21 | 11 | = | 288 | 16 | 8 | x | 23 | 11 | = | 398 |
| 5000 | 240 | 60 | 13 | 8 | x | 14 | 2 | = | 195 | 14 | 0 | x | 16 | 0 | = | 224 |
| 5000 | 83 | 25 | 14 | 3 | x | 19 | 9 | = | 282 | 15 | 0 | x | 20 | 0 | = | 300 |
| 1500 | 300 | 25 | 10 | 10 | x | 11 | 8 | = | 123 | 12 | 3 | x | 11 | 9 | = | 143 |

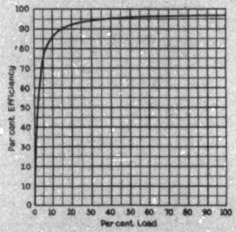

FIG. 9—EFFICIENCY OF 5000-H.P., 0.85-POWER FACTOR, 240-REV. PER MIN., 2200-VOLT, 60-CYCLE SYNCHRONOUS MOTOR FROM TEST DATA

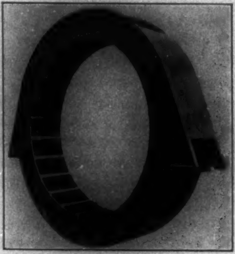

FIG. 10—STATOR FRAME FABRICATED FROM STEEL PLATES AND BARS

## SPEED CONTROL

Control, or rather adjustment, of the speed of a synchronous motor in mill service is of course impractical, and its use must, therefore, be confined strictly to constant-speed mills. This fact also eliminates it from consideration on any so-called constant-speed mill on which a flywheel is necessary, for to get any beneficial effect from the wheel the speed must vary inversely with the load.

The fact that the motor runs at truly constant speed, except for what variation in frequency occurs on the system, is an advantage on some types of mills. For example, if the product from a continuous mill of the type shown in Fig. 3 is cut into lengths by a flying shear, as it leaves the mill, the lengths will be more uniform if the mill speed is absolutely constant than if it varies slightly.

### COST

The cost of a synchronous motor, of the capacity used for main roll drives, complete with exciter and control, is usually less than that of a similarly rated induction motor. For machines of medium capacities, speeds, and voltages, the differential is not great, but for large low-speed units, the synchronous machine is considerably less expensive.

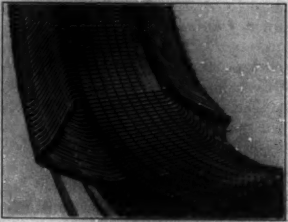

FIG. 11—PARTLY WOUND STATOR, SHOWING METHOD OF BRACING THE COILS

### RELIABILITY AND EASE OF REPAIR

From the standpoint of reliability it can hardly be said that either type of motor has the advantage. A machine any more reliable than the well built mill-type induction motor has proved itself to be, would be difficult to find, but there is no reason why the synchronous motor should not have an equally good record in the years to come.

As far as ease of repairing is concerned, the stators of the two machines are practically on a par. The coils of the synchronous motor are somewhat larger and heavier as a rule, but there are fewer of them. The rotor of a synchronous motor could probably be repaired more quickly than that of an induction machine. The fact that the synchronous motor has a fairly large air-gap helps to facilitate the moving over of the stator for cleaning or repairs.

### CONSTRUCTION

Obviously the details of design and construction described in the following paragraphs apply to motors built by the company with which the writers are associated. The practise of other manufacturers may differ in some respects.

The mechanical and electrical construction of the mill-type synchronous motor is fully as sturdy and reliable as that of the mill-type induction motor. The quantity and kind of the materials used are such that all stresses are kept within a conservative minimum.

The stator frames of the earlier motors of this type are of cast iron. Those built within the past year and a half, however, are fabricated of steel plates securely welded together and braced to form an exceedingly strong and rigid structure. To the inner periphery of the frame are welded steel dovetailed keys. The core laminations are held on these keys and clamped between heavy welded steel finger flanges. Air ducts are provided in the core and complete ventilation is further accomplished by the use of air-slide wedges.

Because of the size and weight of the stator coils in these large motors they are insulated very carefully to protect them from mechanical injury. After their assembly in the stator the end projections are securely laced to insulated steel bracing rings which are supported from the stator frame. The larger machines are supplied with resistance temperature detectors. The stator coils are liberally designed to safely take care of sudden overloads or the condition where the motor may be required to develop its maximum torque as an induction motor.

The rotor spiders of the machines of small diameter are built up of laminations punched from heavy steel plates, those of larger diameter being of cast steel. The laminated pole pieces are either dovetailed into the punched rotor or secured to the cast rotor by means of bolts screwed into steel keys imbedded in the pole pieces.

The field windings are usually of edgewise-wound copper strip. Here again great care is given to the insulation between the turns of the winding, and of the coils as a whole from the pole pieces and rotor spider. One of the recent improvements in design consists in the addition of fins to the ends of the field coils which are made by simply projecting every second or third turn during winding. These fins provide an increased area of radiating surface on the ends of the coils and have proved very effective in reducing the field temperature.

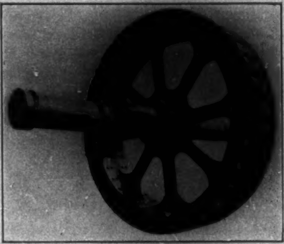

FIG. 12—ROTOR WITH CAST STEEL SPIDER

Since, at times, these motors may be required to develop their maximum torque as induction motors, considerable attention is given to the heat storage capacity of the amortisseur winding, the materials used being such that their strength will be retained at high temperatures. The bars are silver soldered into the end-ring segments. The end-ring segments have bolted joints between poles so that each individual pole may be readily removed from the rotor without disturbing the others.

The specially designed mill-type pedestals are securely bolted to both the base and foundation. They are equipped with babbitted thrust collars when this feature is desired. These pedestals are insulated from the base to eliminate the possibility of shaft currents. The spherical-seat, self-alining bearings may be equipped with temperature relays. A liberally designed ring oiling system insures ample lubrication but in addition, provision is made so that flood lubrication may be applied.

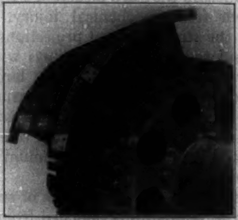

FIG. 13—ROTOR WITH LAMINATED SPIDER

The base is provided with rollers under the carrier plates supporting the stator feet in order that the stator frame may be easily moved in a direction parallel to the shaft. The carrier plates are keyed to the base in order to maintain the alinement of the stator frame during this movement.

Air heaters may be installed in the lower halves of the stator frames of these motors to prevent the possible accumulation of moisture on the windings in case the mill is idle for any considerable length of time.

### CONTROL

A few main-roll synchronous motors are started at full voltage, but most of them are so large that such practise is not desirable because of the resulting demand on the power system. Consequently, an auto-transformer is usually employed to give reduced voltage for starting. For some of the largest machines it has proved desirable to employ two reduced voltage steps in the starting operation, and to meet this condition the combination Korndorfer and reactor method illustrated diagramatically in Fig. 14 has been developed.

The sequence of operations for starting, stopping, or plugging the motor is initiated by the simple movement of the handle of a master switch placed near the mill, and the operation is completed automatically under the control of relays on the control panel.

We will assume that the motor is at rest and that the operator throws the handle of the master switch to the "forward" position. Oil circuit breaker *A* closes at once, establishing the neutral connection of the auto-transformer,—*F* follows immediately, connecting the line end of the auto-transformer to the line and thereby applying the first step of reduced voltage to the motor. With this voltage the motor should start and gradually increase its speed.

When it reaches a predetermined speed, usually from 50 per cent to 75 per cent of synchronism, as indicated by the frequency obtained from a small pilot generator on the main motor, a relay operated in response to the frequency causes breaker *A* to open, and immediately thereafter breaker *B* closes. *B* connects the motor to the line through the reactor. The reactor is so proportioned that the voltage drop across it at the time it is connected in the circuit is sufficient to reduce the voltage at the motor to a value between the line voltage and that given by the auto-transformer tap. As the motor speed increases, the current will drop and the voltage at the motor terminals will rise.

When the motor reaches approximately 95 per cent synchronous speed, as determined by a relay which operates only when the difference between the line frequency and the pilot generator frequency is 5 per cent or less, field excitation is applied, of sufficient value to give approximately unity power factor. This pulls the motor into step, and so reduces the current drawn by the motor through the reactor that the voltage at the motor terminals increases almost to the line value.

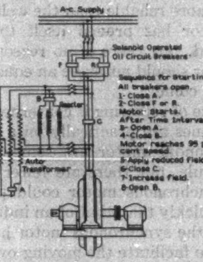

FIG. 14—ELEMENTARY DIAGRAM OF COMBINATION KORNDORFER AND REACTOR METHOD OF STARTING SYNCHRONOUS MOTORS

After a short-time interval, breaker *C* closes, *B* opens, and the field excitation is automatically increased to the full value.

It will be noted that at no time during the sequence of starting operations is the motor entirely disconnected from the line. Furthermore, owing to the use of the reactor, the transition from the second starting voltage to the line is made with extreme smoothness.

Protection is provided against under-voltage, loss of excitation, and failure to synchronize within a definite interval after the master switch is operated.

The control equipment for a synchronous motor involves more oil circuit breakers than does that for an induction motor, but the latter requires a number of large contactors and resistors for its rotor circuit, with relays for controlling the same. Neither is especially complicated in installation or maintenance. So far as the mill operator is concerned, he simply moves the handle on one kind of master switch to start either type of motor.

### INSTALLATIONS

A considerable number of synchronous motors is now installed or being built for main roll service. Those supplied by one manufacturer include the following:

A 9000-hp., 107-rev. per min., 25-cycle, 6600-volt unit is driving a continuous sheet bar mill at the Cleveland plant of the Corrigan-McKinney Steel Company. This motor has a higher continuous horsepower rating than any other motor in industrial service in this country.

Two motors, one 6500-hp., 187-rev. per min. and the other 4000 hp., 83 rev. per min., 25 cycles, 6600 volts, form part of the drive of a continuous skelp mill at the Bethlehem Steel Company's Sparrows Point plant.

A 5000-hp., 240-rev. per min., 60-cycle, 2200-volt synchronous motor is being installed to drive a tube piercing mill at the Standard Seamless Tube Company's plant at Economy, Pa.

The Continental Steel Corporation, Kokomo, Indiana, has purchased a 5000-hp., 100-rev. per min., 60-cycle, 2200-volt motor to be used in driving a continuous sheet bar mill.

The Copperweld Steel Company of Glassport, Pa. will use three 60-cycle, 2300-volt synchronous motors, one 600-hp., 400-rev. per min., one 600-h. p., 514-rev. per min. and one 600-h. p., 900-rev. per min. to drive various merchant and rod mill stands.

Two 400-hp., 720-rev. per min., 60-cycle, 4600-volt motors have been purchased by the Higgins Brass and Manufacturing Company, Detroit, Michigan, to drive brass and copper mills.

Another manufacturer has built several synchronous motors for seamless tube mill service, some of them being for piercing mills and some for tube rolling mill drives.

### CONCLUSION

The foregoing discussion, we believe, has made clear that the synchronous motor is a real competitor of the wound-rotor induction motor for some types of main roll service. The number of installations which have been made within a comparatively short space of time certainly proves this contention. The synchronous motor has certain definite advantages, such as better power factor, efficiencies, and cost, which make it very attractive. Its starting characteristics are not so good as those of the induction motor, but for many drives they are sufficient and on those mills it can often be used to advantage.

It seems safe to predict the widely increasing use of the synchronous motor in mill service, and with this prediction goes the hope that such motors will be applied, designed, and built only with a full knowledge of the demands of the load and the limitations of the motor.

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## Discussion

**H. V. Putman:** Mr. Berkshire classifies the application of synchronous motors to cold strip rolling mills as undesirable because of the high starting torque (usually 200 per cent) required. We already have one installation of a synchronous motor on a cold strip mill starting up under 200 per cent of normal torque and giving entire satisfaction.

The principal problem in applications of this kind is to obtain the necessary starting torque with a reasonable inrush kv-a. Recent developments in synchronous motors indicate that it is possible to obtain these high values of starting torque with little more inrush kv-a. than would be required by a normal wound-rotor motor.

As an example, we are now building a low-speed synchronous motor for driving a ball mill in a rock-crushing plant. This mill requires approximately 200 per cent starting torque and slightly over 100 per cent pull-in torque. This synchronous motor will deliver 200 per cent starting torque with about 390 per cent inrush. In fact, the starting torque may be varied at will from about 160 per cent torque to 235 per cent, the inrush being almost proportional to the torque. The calculated pull-in torque is 125 per cent.

Now this is almost as good torque per kv-a. as would be obtained from an ordinary slip-ring motor. While the slip-ring motor will give 100 per cent torque with 100 per cent kv-a. to get 200 per cent torque at starting it is necessary to reduce the resistance in the rotor circuit so that its power factor is much poorer. Also, it should be remembered that the normal kv-a. on which the per cent inrush is based, is figured on a power factor considerably less than unity, especially on low-speed machines. The slip-ring motor would therefore give 200 per cent starting torque with an inrush of about 350 per cent based on unity-power-factor kv-a. This is to be compared with the 390 per cent inrush for the special synchronous motor mentioned above. This leaves the slip-ring motor but little advantage for applications requiring high starting torque.

While some features of this new motor are still experimental, it may be said at this time that it is of the salient-pole construction and has the high efficiency and low exciter capacity characteristic of machines of this type.

In view of these recent developments, I think it is reasonable to predict that in the near future synchronous motors will be recommended and used for any constant-speed, non-reversing drive, regardless of the starting duty.

There are two other points I should like to comment on: the matter of power factor and the construction of damper windings.

I think most users of synchronous motors have the idea that unity-power-factor motors are cheaper than 80 per cent power-factor machines. This is ordinarily true, but it is not true of motors having a pull-out torque of between 250 per cent and 300 per cent. An 80 per cent motor costs no more than a unity-power-factor motor when the pull-out torque is between these values. Invariably the electrical manufacturer prefers to supply the leading-power-factor machine because it has a lower magnetizing current and hence better starting characteristics. Leading-power-factor motors are therefore to be recommended when high pull-out torque is required. When no corrective kv-a. is required, then a 90 per cent power-factor machine represents a desirable compromise.

The best damper winding, judged from its heat-storage capacity, is one in which the damper bars are buried in the pole iron for their entire length, no portion being left exposed to the air. This is because practically all the heat is generated in the damper bars. They have small heat capacity in themselves, but when buried in the iron of the pole face the iron conducts the heat away from the bars into the pole body, where there is unlimited capacity for storing it during the starting period. Experience shows that a portion of the damper bars exposed to the air is the first part to fail when a damper winding is allowed to burn out.

A 4000-hp. steel-mill motor now being built has a damper winding in which the bars are buried in the pole iron for their entire length.

**B. A. Behrend:** The use of synchronous motors for the driving of rolling mills is certainly greatly to be commended. The synchronous motor is more robust and less liable to breakdown and, when in need of repair, such repair is more readily and easily made. Its overload margin can be made at least equal to that of the induction motor; its power factor can be made anything required, leading or lagging; its speed can be made low as there is not the same difficulty in taking care of a large number of poles which causes the low power factor of the induction motor. On this point the simple rule which I gave years ago ("The Induction Motor," its Theory and Design, now available in a new edition as "The Induction Motor and Other Alternating-Current Motors," McGraw-Hill Book Co., 1927) might be useful to the steel engineers who are not familiar with the design of electrical machinery. This rule is: Maximum Power Factor $= 1:(2\,\sigma + 1)$, where $\sigma$ is the leakage coefficient which is proportional to the air gap multiplied by a constant dependent on design and divided by the pole pitch. For 5000 hp. at 100 rev. per min. and 60 cycles there are required 72 poles which, with a rotor diameter of 15 ft., corresponds to a pole pitch of about 8 in. Given an air-gap of 1/16 in., a leakage factor of about 0.08 results. Substituting this for $\sigma$ in our formula for the power factor, we obtain $(\cos \varphi)_{max} = 1:(1+2\times.08)$ or 0.86. Such motors have been built and the small air-gaps have operated satisfactorily but that is a different story from recommending them when other solutions are available. Next, the synchronous motors are more readily wound for high voltage and the stator windings are more secure for the same voltage; there remain as the principal difficulties the starting torque and the hunting in regard to which the induction motor is superior.

The starting torque of the synchronous motor could be raised by methods of pole face windings with resistance and slide rings but such motors have not been popular, a characteristic which appears to apply to most "combination" devices. There remains the alternative of employing clutches which allow easy starting and much will be done in this direction. There are in use abroad centrifugal pulleys or pulleys with centrifugal devices in them, which permit starting without load. Similar schemes will be used here as soon as the demand for them is going to be felt which will be in the immediate future.

Thus there remains the characteristic of hunting which can be overcome readily by calculating the natural period of oscillation of the synchronous motor at the excitations at which it operates and increasing or decreasing the mechanical inertia of the revolving parts so as to secure a coefficient of resonance which corresponds to a small increase in the amplitude of oscillation of the rotor. This assumes the knowledge of a period of forced oscillation which is not always capable of being estimated. It can be estimated in motors driving compressors, for instance. As the synchronous motor requires a powerful low-voltage winding on the rotor, this winding will act as a circuit in which the energy of oscillation can be quickly dissipated thus leading to a rapid decay of the oscillation without causing disturbance in the system. The summary favors preponderantly the synchronous motor over the induction motor for slow-speed low-starting torque, non-reversible applications.

**F. C. Hanker:** The following table gives practically a complete list of synchronous motors of 300 hp. and above installed annually to drive various mills in the metal industry.

| Year | Hp. | Units |
|---|---|---|
| 1913 | 500 | 1 |
| 1918 | 1350 | 1 |
| 1924 | 1600 | 3 |
| 1925 | 18100 | 13 |
| 1926 | 12000 | 3 |
| 1927 | 27100 | 17 |
| | 60650 | 38 |

The first main-roll electric drive installed in the United States was put in service in 1905, and by the end of 1924 the total electric hp. on main-roll drives was approximately 1,354,600, of which 3450 hp. was synchronous motors. Since 1924 the total hp. of electric motors installed for driving rolling mills has increased 42 per cent and the synchronous-motor hp. has increased 1750 per cent. At the present time the synchronous-motor hp. on rolling mills is approximately 60,000, practically all of which has been placed in the last three years.

A partial list of types of mills now being driven by synchronous motors follows:

Continuous sheet bar and billet mill
Continuous skelp mill
Piercing mill
Tube rolling mill
Tube rolling and sinking mill
Merchant roughing mill
Merchant finishing mill
Cold sheet mill
Copper rod mill
Brass and copper sheet mill.

In addition to the above, some smaller synchronous motors are being used for wire drawing.

Two or three of the above types are generally driven by wound-rotor induction motors in connection with flywheels. By properly proportioning the synchronous motor a successful application can be made on these mills, omitting the flywheel and using synchronous motor drive. This is, of course, only practical when the power system supplying the motor is of sufficient size that the mill peaks are not objectionable, as these peaks cannot be equalized if the synchronous motor is used. These peaks on the motor will increase the r. m. s. value of the load so there is needed a somewhat larger synchronous motor, than if a type utilizing a flywheel were used. This is partly offset by the decreased friction and windage losses incident to the omission of the flywheel.

It has been stated that the cost of a steel-mill synchronous motor is usually less than a similarly rated induction motor. Therefore, the fact that in some special cases a somewhat larger synchronous motor may be required to replace successfully a given size induction motor, does not seriously handicap the synchronous-motor installation from the cost standpoint.

The most recent application of a synchronous motor for rolling-mill service includes a 4000-hp., 2200-volt, 3-phase, 60-cycle, 450-rev. per min. unit for driving a continuous billet-roughing mill.

It would appear from the above that the author's prediction of a widely increasing use of synchronous motors in mill service is amply justified.

**B. G. Jamieson:** I should like to know why, in a recent installation of a large steel mill in Chicago, on which I understand several large manufacturers were consulted, a slip-ring motor was finally chosen, a 6000-hp. motor.

**G. A. Chutter:** (communicated after adjournment) The writers of this paper state that the synchronous motor is not adaptable to drives requiring reversal or speed adjustments. They further limit the field of the synchronous motor to drives not requiring a fly wheel, and exclude this type of motor from certain applications where the metal is cold-worked and the motors must be capable of starting under 200 per cent torque with metal in the rolls. Such drives are the cold strip mills and cold sheet mills. Approximately 90 per cent of the cold strip mills are driven by d-c. motors having a speed range of two-to-one, or greater. This speed range is necessary if the mill is to roll a wide variety of products, and the synchronous motor is barred from this field on account of its inability to supply this speed range, as well as on account of the high inrush kv-a. incident to the starting torque required.

In the case of the cold sheet mills there may be some possibility of applying the super-synchronous motor as described by Mr. Berkshire. This motor requires very little starting torque, consequently the stator may be brought up to speed with very small kv-a. inrush. The load is brought up to speed by applying a brake to the stator, so that a minimum peak demand is made on the line. This motor has the disadvantage of being somewhat more expensive than the synchronous motor, and having, in addition to the usual control equipment, a stator brake. This motor has given a very satisfactory account of itself in the cement mills.

Attention should not be diverted too much from the requirements of the major part of the field in which the synchronous motor is the logical contender, to a relatively small part of the field where its choice is more questionable. In the major part of this field, as outlined by Messrs. Winne and Berkshire, it is not so much what torque the synchronous motor will develop at full voltage as the torque per kv-a. that the motor will develop. Load curves similar to that shown in Fig. 5 of this paper will be found very satisfactory for most of these applications. Without drawing more than 100 per cent kv-a. we can have a starting torque of 58 per cent on the 41.5 per cent voltage tap of the auto-transformer, and a "pull-in" torque of 61.5 per cent at 100 kv-a. on the 75.5 per cent voltage taps of the auto-transformer. These torques are satisfactory and the motor may be connected to the line without exceeding 100 per cent kv-a. It will be noted from the data shown in Fig. 5 that the torque per ampere at starting is approximately in the ratio of 1 to 1.73.

**W. T. Berkshire:** I should like to corroborate Mr. Putman's statement regarding the cost of synchronous motors required to develop anything over 200 per cent pull-out torque.

We have found it true, also, that it costs no more to build an 0.8-power-factor machine than it does a unity-power-factor machine to develop this pull-out torque. This 9000-hp. motor to which I have referred was built for unity power factor wholly because of the customer's wishes. The power factor in his plant was very nearly unity and he did not want any leading power factor because it would mean just as much drain on his generating system as if the power factor were lagging.

In order to obtain the pull-out torque on this machine, the air gap was ⅞ in.

When speaking of machines required to develop 200 per cent starting torque, I had in mind the ordinary, straight synchronous motor as we usually understand it.

We have also built a number of smaller machines for cold strip and cold sheet mills of the super-synchronous motor type. In this type of machine, the stator revolves during the starting period. It is started as an induction motor with the stator revolving, and after the stator comes to synchronous speed and excitation is applied with the rotor standing still, the brake is applied to the outer periphery of the stator and the load gradually brought to speed. This machine, of course, can develop the whole of its pull-out torque throughout the whole of the starting of the load from initial start to synchronous speed.

We have never tried to apply this machine to motors having a range of 6000, 8000, or 9000-hp., but there is no reason why it should not be done. For that reason, I don't see why eventually we should not be allowed to drive cold strip mills with the synchronous motor.

# The Chicago Regional Power System

BY E. C. WILLIAMS[1]
Member, A. I. E. E.

**Synopsis.**—*This paper is a general description of the interconnected power systems in the region surrounding and including Chicago as a center. The electrical energy generated in this region in 1926 was over 4,000,000,000 kw-hr. and the combined generating capacity of the three largest companies was 1,340,000 kw. The paper outlines important features of major stations and transmission and distribution systems and gives plans for the future developments. It also explains the contract for interchange of energy among the three largest companies.*

* * * * *

THE design of any electricity supply system should be coordinated with the geographical, industrial and social character of the community which it serves. The electricity supply systems of the Chicago territory are in a rather unusual position in this respect because of the potential resources, both industrial and commercial, of the territory served. Chicago, due to its location, has been since the beginning in an excellent position to command an enormous growth. Being near the center of a great agricultural district with coal, ore, lime-stone, and other deposits close at hand, with excellent transportation facilities both by rail and water, it is not surprising that it has grown from a village of 4500 people in 1840 to a city with a population of 2,700,000 at the time of the last official census and now estimated at 3,700,000. The Chicago Regional Planning Association estimates that by 1930 there will be a population of 4,891,600 within a radius of approximately 50 mi. of Chicago.

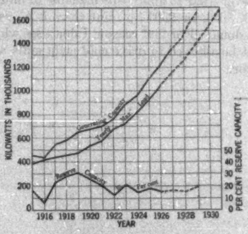

FIG. 1—GENERATING CAPACITY AND MAXIMUM LOAD IN THE CHICAGO REGION

This industrial and commercial activity has created a demand for electric power which has been met by what has been called "the greatest pool of power in the world." According to the U. S. Geological Survey 73,791,064,000 kw-hr. of electrical energy were generated in 1926 by utility companies in the United States and 4,128,455,000 kw-hr. or 5.6 per cent were produced in the Chicago region.

The principal companies serving this area are as follows: Commonwealth Edison Company, Public Service Company of Northern Illinois, Northern Indiana Public Service Company, and Illinois Power & Light Corporation. The combined load of the three larger Companies, namely, the Commonwealth Edison Company, the Public Service Company of Northern Illinois and the Northern Indiana Public Service Company all of which are operated by the same interests has shown a growth in the last decade as shown in Fig. 1, the maximum load being below 400,000 kw. at the beginning of 1916 and being slightly above 1,000,000 kw. at the peak load period in 1926.

The stations of these three companies with their present capacities are shown in the following tabulation:

PRESENT GENERATING STATION CAPACITIES IN THE CHICAGO REGION

| | | |
|---|---|---|
| **Commonwealth Edison Company** | | |
| Crawford Avenue Station | 324,000 kw. | |
| Calumet Station | 187,500 | |
| Fisk Street Station | 230,000 | |
| Northwest Station | 165,000 | |
| Quarry Street Station | 84,000 | |
| Miscellaneous | 65,060 | |
| | | 1,055,560 kw. |
| **Public Service Company of Northern Illinois** | | |
| Waukegan | 110,000 kw. | |
| Joliet | 50,000 | |
| Blue Island | 43,000 | |
| Miscellaneous | 34,790 | |
| | | 237,790 kw. |
| **Northern Indiana Public Service Company** | | |
| East Chicago | 26,400 kw. | |
| Miscellaneous | 20,425 | |
| | | 46,825 kw. |
| GRAND TOTAL | | 1,340,175 kw. |

GENERATING CAPACITIES TO BE ADDED IN THE NEXT TWO YEARS

| | | |
|---|---|---|
| 1928 | Crawford Avenue | 100,000 kw. |
| 1928 | Powerton (Partly for use of Chicago Region) | 52,000 kw. |
| 1929 | State Line | 200,000 kw. |

The Crawford Avenue Station with a capacity of 324,000 kw. is at present the largest station in the region and is capable of being developed to perhaps three quarters of a million kilowatts provided there is a certainty as to the amount of condensing water that can be depended upon from the Drainage Canal. A view of the turbine room of this station is shown in Fig. 2.

Another large generating station is the Calumet

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Station located on the Calumet River having a capacity of 187,500 kw. which is already utilizing about all available water in the Calumet River and has consequently reached its ultimate capacity. Other large stations in Chicago are the Northwest Station, the Fisk Street Station, and the Quarry Street Station which are older stations and on account of water conditions and property limitations can only be increased in size by the replacement of present units with more efficient units of larger size.

The main outlying stations are at Waukegan and Joliet with present capacities of 110,000 kw. and 50,000 kw. respectively. The site at Waukegan is capable of development to approximately 1,000,000 kw. The site at Joliet is capable of similar development providing the condensing water available from the Drainage Canal is not limited as mentioned in connection with the Crawford Avenue Station.

As to future generating stations which will furnish energy to the Chicago region two large ones are already under construction, namely the Powerton Station located southwest of Peoria near Pekin on the Illinois River and the State Line Station on Lake Michigan at the Illinois-Indiana State Line. Property has been acquired in Michigan City and also at a location southwest of Chicago on the Drainage Canal for the construction of future generating stations but it has not been definitely announced when construction will begin at either of these points. The Powerton Station is rather unique in that it is jointly owned by four companies which are the Central Illinois Public Service Company, the Illinois Power and Light Corporation, the Public Service Company of Northern Illinois, and the Commonwealth Edison Company. These companies have pooled their comparatively small requirements in the immediate vicinity and are erecting this modern efficient station. The first unit with a capacity of 52,000 kw. is scheduled for completion during the summer of 1928. In connection with this project a 132,000-volt transmission line is now being built from Joliet through Oglesby and Kewanee to the Powerton Station for interconnection with the Chicago pool.

Fig. 2—Turbine Room, Crawford Avenue Station

With regard to the State Line Station, the tract of land procured is adequate and plans are being made for a station with an ultimate capacity of a million kw. or more. This station is to be owned jointly by the Commonwealth Edison Company, the Public Service Company of Northern Illinois, the Northern Indiana Public Service Company, and the Middle West Utilities Company. The first unit, scheduled for completion in 1929, is to have a capacity of 200,000 kw. and will consist of three turbo generator sets each having a capacity of approximately one-third of the total arranged as shown in Fig. 3. Steam at 650 lb. pressure is admitted to a single high pressure turbine which exhausts into two identical low-pressure turbines each taking half of this exhaust steam.

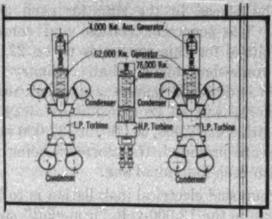
4,000 Kw. Aux. Generator
62,000 Kw. Generator
76,000 Kw. Generator
Condenser
Condenser
L.P. Turbine
H.P. Turbine
L.P. Turbine
Condenser
Condenser

Fig. 3—Unit No. 1, State Line Power Station

In the design of this unit, means are provided whereby any one of the three turbines may be taken out of service and the other two continued in operation thus overcoming the common objection from an operating standpoint of such a large capacity being contained in one unit. At present five such units of 200,000 kw. each are planned for this station with suitable transmission facilities for carrying away the energy. Contrast with these units, the 30,000-kw. units which were installed at the Calumet Station as late as 1921, which

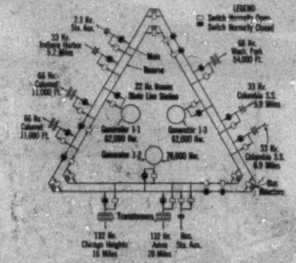
LEGEND
□ Switch Normally Open
■ Switch Normally Closed
2.3 Kv. Sta. Aux.
33 Kv. Indiana Harbor 5.2 Miles
Main
Reserve
66 Kv. Wash. Park 54,000 Ft.
66 Kv. Calumet 11,000 Ft.
22 Kv. Busses State Line Station
33 Kv. Columbia S.S. 5.9 Miles
66 Kv. Calumet 11,000 Ft.
Generator 1-1 62,000 Kw.
Generator 1-3 62,000 Kw.
Generator 1-2 76,000 Kw.
33 Kv. Columbia S.S. 6.9 Miles
Bus Reactors
Transformers
132 Kv. Chicago Heights 16 Miles
132 Kv. Aetna 28 Miles
Res. Sta. Aux.

Fig. 4—Bus and Feeder Connections, 1929 State Line Station

were then the largest ever built for this territory.

The electrical installation also is rather unusual in that the generator bus will be completely out of doors and entirely enclosed by metal so that no physical contact can be made with any live parts. Fig. 4 shows the schematic arrangement of the bus which is a double ring bus divided into three sections, one generator supplying each section with suitable reactors and oil circuit breakers between sections. It is so laid out that as future generators are added one additional bus section will be placed in the ring for each additional generator. The generator voltage and consequently the bus voltage for this station is to be 22,000-volts which is somewhat higher than ordinary practise. The station is designed purely as a generating station and the energy will all be transmitted away in large quantities either at 33,000, 66,000, or 132,000 volts. No line busses are provided, transformers being installed integral with each individual line.

Another unusual electrical installation is to be found at Waukegan in the 12,000-volt "iron-clad" switchgear used in connection with the recently installed 50,000-kw. (58,825 kv-a.) unit. Although equipment of this type has previously been used in connection with lower voltage bus work at several substations in the Public Service Company territory, the Waukegan installation is the first used in a generating station in this country in connection with such a large capacity. The largest switches are rated at 1,500,000 kv-a. interrupting capacity and 3000 ampere carrying capacity. This installation which is indoors completely encloses in metal all of the bus work and switching equipment and thus reduces the hazard to operators in coming in contact with live parts as well as providing several other important advantages. This apparatus is very compact thus simplifying the building requirements both at the time of installation and at times when it is necessary to make additions or increase capacity. It is shipped in units or groups of units with practically all wiring, taping, and adjustments completed in the factory where workmanship and labor costs are naturally more favorable than in the field. Fig. 5 shows a view of this equipment.

FIG. 5—IRON-CLAD SWITCHGEAR ON GENERATING BUS, WAUKEGAN STATION

In general this matter of switching equipment is becoming quite serious especially as to interrupting capacities. It would seem that the development of high interrupting capacity switch gear has not kept pace with the growth of the business and consequently the requirements of the supply companies. The result has been that the supply companies have quite often been forced to make costly changes in structures as well as retire comparatively new equipment due to radical changes in design on the part of the manufacturers or unsatisfactory performance of equipment.

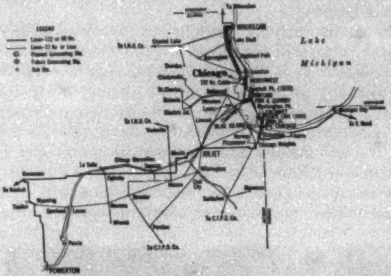

FIG. 6—TRANSMISSION SYSTEM IN CHICAGO REGION AS PROPOSED FOR 1928

The transmission system in the Chicago region has had a very interesting development. Practically all of the stations have been interconnected. Within Chicago the system has developed from one 2250-volt transmission line in 1897 to the network of 12-kv. and 66-kv. underground cable of today. The outlying stations are either connected with each other or with the Chicago stations by means of a 132-kv. net-work with an auxiliary 33-kv. system. Fig. 6 shows the system as it will appear in 1928. It is to be noted that superpower interconnections have already been made with neighboring companies on practically all sides.

The transmission of large blocks of power through densely populated areas will soon require the extensive use of high-voltage underground cables. A move in this direction is to be noted in the six mi. of 132-kv. underground line connecting the Northwest Station in Chicago with the overhead transmission line from Waukegan at the city limits. This line consists of three single-conductor, hollow-core, oil-filled cables with a capacity of 90,000 kv-a. and has been in satisfactory operation since June of this year.

In this same connection there is still room for improvement in the design of overhead transmission lines, especially in regard to mitigating the effects of lightning. Considerable progress in this respect however has been made during the last few years by the use of ground wires, arc-controlling devices, and the lowering of the plane of the conductors. The following tabulation summarizes the experience with ground wires in this territory:

EFFECT OF GROUND WIRE ON 132-KV. OVERHEAD LINE INTERRUPTIONS CAUSED BY LIGHTNING

| Line | | Interruptions | | | | |
|---|---|---|---|---|---|---|
| No. | Location | Length miles | 1924 | 1925 | 1926 | 1927 |
| 1. | Waukegan—Niles Center.. | 27.5 | 28* | 20* | 14* | 0‡ |
| 2. | Waukegan—Northwest Station................ | 31.1 | | | | 1*¶ |
| 3. | Waukegan—Kenosha...... | 20.7 | | | | 0‡ |
| 4. | Joliet—Chicago Heights... | 29.8 | | 9 | 29 | 1‡ |
| 5. | Chicago Heights—108th St | 14.4 | | 7¶ | 7¶ | 6¶ |
| 6. | 108th Street—Aetna...... | 26.7 | | 0†‡ | 0†‡ | 1†‡ |
| | TOTAL................ | 150.2 | 28 | 36 | 50 | 9 |

*Equipped with arcing-rings.
†13.8 mi. equipped with arcing rings.
‡Ground wire installed over circuit.
¶Ground wire installed over circuit on opposite side of tower.

The improvement brought about by the use of ground wires is conspicuously evidenced in the case of lines No. 1 and No. 4 where the ground wires were installed after some experience without them.

I wish now to refer to the "interchange energy contract" between the Commonwealth Edison Company, the Public Service Company of Northern Illinois, and the Northern Indiana Public Service Company by means of which an equitable interchange of energy and capacity is obtained. The capacity of all three companies is placed in a so-called "power pool" from which each company may draw in order to supply its load. The principal purpose of the arrangement is to enable the entire load of the three companies to be carried by the most efficient generators regardless of their ownership, leaving the less efficient to carry the peaks and to act as reserve. The energy is paid for by each consuming company at various rates depending upon the stations from which the energy is supplied. The investment charges are taken care of on a basis of demand and capacity illustrated by the following typical example. The figures given in the following tabulation show the generating capacity and previous maximum load for each company as of December 31, 1926, one of the monthly billing dates. The total generating capacity of 1,199,500 kw. is allotted to the three companies in the ratio of their previous individual maximum demands shown in the second column.

| | Generating capacity 12-31-26 | Previous maximum demand 12-31-26 | Demand at time of system max. 12-15-26 |
|---|---|---|---|
| Commonwealth Edison Co. | 965,000 kw. | 864,300 kw. | 864,300 kw. |
| Public Service Co. of Nor. Ill.................. | 187,800 | 139,800 | 135,600 |
| Nor. Ind. Public Service Co. | 46,700 | 43,600 | 40,200 |
| TOTAL.............. | 1,199,500 kw. | 1,047,700 kw. | 1,040,100 kw. |

The company actually owning generating capacity, shown in the first column, in excess of its allotment receives the carrying charge on this excess from the other two companies which own less than their allotments. A limit of 20 per cent reserve on the total system is set up beyond which no credit is given.

I now wish to refer briefly to studies of the transmission network which are being made in the Chicago region. A plan has been adopted wherein the entire region including the City of Chicago has been divided into areas for distribution purposes. All the energy for each of these areas is to be supplied from one source. This source may be a generating station or a large or major distribution center receiving its supply over either 66,000 or 132,000-volt transmission lines. The energy is to be distributed at 33,000 or 12,000 volts from this main source to the various substations in the area for re-distribution. The substations in one area will not, in general, be connected to those of another area although some emergency ties may be needed which will normally be operated open. With this system, the relay problem will be materially simplified and trouble may be more easily segregated than with the system in use at present wherein the various substations are connected to several sources. The duty on oil circuit breakers will also be considerably reduced. Fig. 7 shows the proposed scheme applied to a part of the territory of the Public Service Company of Northern Illinois. The high-voltage transmission lines supplying the major distribution centers are not shown. The groups of radiating loops from the major distribution centers conspicuously define the respective areas.

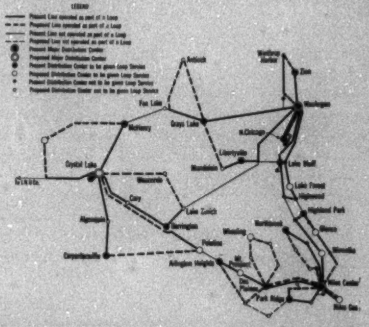

Fig. 7—Proposed 33,000-Volt Area Transmission Systems
Public Service Company of Northern Illinois, North Part of Territory

Fig. 6 shows two such major distribution centers planned for Chicago located at Washington Park and Humboldt Park to be supplied at 66,000 volts and scheduled for completion in 1928 and 1929 respectively. They are in addition to those already established at the various Chicago generating stations. By 1928 the area surrounding Chicago will have several similar major distribution centers other than the generating stations, the most important of which will be located at Niles Center, Bellwood, Chicago Heights, Aetna, Michigan City, Oglesby, and Kewanee.

Transportation in the Chicago Region accounts for a considerable part of the demand for electrical energy. Of the 1,040,100 kw. total system demand which occurred December 15 of last year nearly 350,000 kw. was supplied to the electric railways in and around Chicago. The first and only steam road in this region to electrify is the Illinois Central Railroad which completed the electrification of its suburban service in June of last year. This customer's maximum demand to date has been 22,864 kw. The railroad operates its cars at 1500-volts direct current supplied by seven substations, five of which are owned by the Commonwealth Edison Company and two by the Public Service Company of Northern Illinois. The conversion to direct current is accomplished in some cases by mercury arc rectifiers and in others by units of two 750-volt rotary converters in series. Fig. 8 shows the Vollmer Road Substation at Flossmoor, installed by the Public Service Company of Northern Illinois for supplying this railroad and the light and power business in that vicinity. This particular substation was thought of interest inasmuch as it is located in a residential territory and in order to harmonize with the developments in that region a building of Spanish design which should not detract from the general surroundings was erected. The first impression might be that such a design is expensive but if the architect is ingenious in the use of materials this need not be so. In fact the cost per cubic foot of content of this particular substation, was practically the same as that of another substation erected at the same time following the ordinary type of construction.

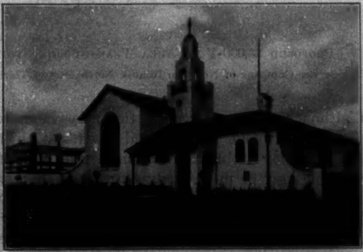
FIG. 8—VOLLMER ROAD SUBSTATION

Fig. 9 shows the Glen Ellyn Substation supplying direct current to the Chicago, Aurora, & Elgin Railroad where harmonizing architecture was used again.

In this presentation I have tried to point out the problems existing in this region with the idea of bringing them to the attention of engineers generally as these problems are not peculiar to this locality but are being encountered in similar metropolitan areas. Engineers connected with power developments in such regions should be on the alert to so carry on system design that future demands may be met at reasonable cost and with a minimum of obsolescence.

It may be regarded by some as highly optimistic but it is not inconceivable that sometime in the future the dictates of our customers may make intolerable the voltage dips and momentary interruptions due to lightning discharges and emergencies, the elimination of which we are prone to regard as insurmountable. It is to such problems that I commend the energy of the engineer for scientific study in order that the quality of service we render may continue to improve and that our system may be competent to meet the requirements of the public which are rightfully becoming more exacting year by year.

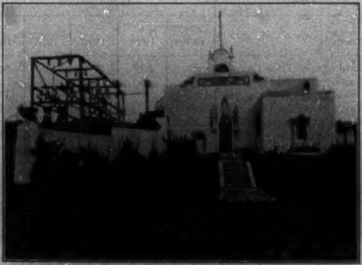
FIG. 9—GLEN ELLYN SUBSTATION

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## Discussion

**H. B. Gear:** One of the subjects which we have just heard discussed is one which has been a large factor in the development of electricity supply in Chicago. I refer to the interchange energy contract, which is in effect between these companies.

The unification of the power supply in the Chicago district did not become effective until the details of this contract were worked out. The effect of this contract is to permit these companies to work together in the development of their physical plant almost as if they were owned and managed by one company.

Before such a contract was in effect, each company tried to plan for its own reserve capacity and its own generating stations without great regard to the requirement or reserve capacity of its neighbors.

Under the operation of this contract no company proceeds to install any generating capacity without the knowledge of the other companies, and whatever is done anywhere within the district is done in view of the total reserve requirements of all the three companies in this district.

This, of course, makes it necessary that there be transmission-line capacity between the stations having reserve capacity and those having no reserve or a deficiency in capacity, in order that the large units installed at points where there is not enough demand to load them may be made available at those points where there is more demand than there is capacity to supply it.

This interchange arrangement is perhaps the most important feature described in Mr. Williams' paper.

**J. L. Hecht:** It seems to me that the problems in connection with a regional development of power system naturally divide themselves into two classes. One might be called the physical problems and the other the contractual.

So far, my own observation has been that the physical problems are the simpler. I feel that we are still in the infancy of this sort of development and there is a great deal to be done. One of the still unsolved physical problems is the one of placing the load on a large interconnected superpower system where we may want to place it. There has been discussion of installing at various points phase-displacement equipment, although up to the present time I don't believe there have been any developments along these lines. However, it appears that that problem will be taken care of.

With regard to the contractual problem, there are still many phases of the superpower contract problem to be worked out. While great strides have been made not only here but in other parts of the country in connection with the working out of contracts, I think that it is a matter to which the engineers should devote considerable thought so that advantage may be taken of their detailed knowledge of the problems that go with power-station and transmission operation.

Taking up another subject, I should like to refer to Fig. 1 of Mr. Williams' paper. I think one of the very important things brought out in that figure is the direct effect of a superpower system on the amount of capital that is tied up in reserve capacity. The lower curve giving the reserve capacity shows that in 1916 the curve was very low. We all know that was the result of war conditions. We were getting along without spending money, without installing necessary reserve capacity, and with taking a certain chance on "getting by." That was followed by a period of installing capacity with the result that the reserve ran rather high. Starting in about 1923, when the superpower interconnections were getting well under way in this region, the curve of reserve capacity became very much stabilized and for the six-year period following 1923 and running through 1929—because we know now what will be done in that period—the curve is almost flat. In other words, this curve illustrates the frequently made statement that having trunk-line interconnections between generating stations makes reserve capacity at any point available to the entire system.

**T. G. LeClair:** This question of interconnection brings up a number of problems which have heretofore not been given as much thought as they should be given.

One thing is that with the development of this large number of interconnecting lines we may sometime reach a limit as to how far we may go.

Mr. Williams in his paper made a statement that the development of switch gear is not keeping pace with the development of systems. This statement at present is quite true because with the development of systems and the development of the interconnecting lines we tie together capacities much more rapidly than we increase the load. We may for example add 50 per cent to the load while at the same time the amount of generating capacity which is tied together in one network may increase three or four times and consequently the interrupting capacity of these switches must be very much higher than it would be if it merely increased in proportion to the load.

So we have reached problems which become not only engineering, but economic, and I think these problems in the development of switch gear are up to the utility men as well as to the engineers of the manufacturers. If we go on developing switch gear with greater and greater interrupting capacities, it is quite possible for the manufacturers to do so, but by so doing they must increase the size and cost of this gear to such an extent that it may be much cheaper to separate the system into a number of parts than to go on paying more and more for this switching equipment regardless of the load it must carry. This problem first reaches us in the metropolitan areas where we have large capacities connected by short lines. As Mr. Williams mentioned, we have well over 1,000,000 kw. in Chicago, and the development of switch gear to interrupt this current is no simple question.

There remain two solutions. One of them is to separate the system into a number of small integral parts and sacrifice the benefits of reserve due to diversity between such sections, and the other is to develop a system which will not require an increase in size of switch gear due to the increase in capacity. To my mind, the second solution requires the development of a system wherein the fault current may be differentiated from the load current.

In the higher-voltage interconnections which we are just now developing, particularly in Chicago, the 66,000-volt cable, interconnecting stations must necessarily be single-conductor at the present stages of development. At the same time we can very rapidly make all our switching stations isolated-phase. By making the switching stations isolated-phase and transformers single-phase, and with single-conductor cable all system faults must begin as phase-to-ground and the fault current is then limited by the use of neutral resistors. By doing this we have made it possible to limit the fault currents on our proposed 66,000-volt system to slightly over 1,000,000 kv-a., while if we went on with the three-phase system, within the next five or six years we would have to interrupt between 4,000,000 and 5,000,000 kv-a. which would undoubtedly produce a problem for the manufacturers in the development of the switch gear. We have utmost confidence that they could develop this gear, but I doubt very much if we would be able to pay for it and consider our money well spent.

**F. C. Hanker:** I had not intended to make any comment on the particular point that Mr. LeClair raised, but in justice to the manufacturer we should consider the situation in connection with interrupting devices.

The operating companies, due to load conditions and the growth of their systems, have been forced to expand and interconnect and have concentrated energies far beyond what was expected when the equipment was originally installed. As Mr. LeClair says, devices of higher interrupting capacity can be built and are being built, but at higher cost. You cannot expect to control the increased energy released in a fault on a modern system and expect to control it safely with the small interrupting devices that were installed in the days when the stations were much smaller.

There is one other factor to consider. The operating companies should begin to consider the effect of the fault current on the operation of the system as a whole. If you can get the fault off a large interconnected system, such as in the Chicago region, in sufficiently short time to prevent the phase displacement of a different generating station or generating unit, then you can continue to supply the load without interruption. With the ordinary conditions we have today you have to interrupt the fault energy on the order of 0.2 sec. to avoid a displacement that is serious.

A number of companies that are operating interconnected are making plans to limit the amount of energy they can concentrate on their higher-voltage lines to a value of kv-a. on the order of 2,500,000. Breakers of that capacity are available in those voltages. Similarly on lower-voltage networks they have reduced that limitation largely for the reason that Mr. LeClair states, that there is an economic limit you can afford to put into switching devices.

You cannot continue to increase the generating capacity and the resultant energy in the fault and still expect your present interrupting equipment to care for the more severe service.

**H. L. Wallau:** The company with which I am associated makes it a practise not to parallel its 132-kv. lines directly. All such lines are paralleled only on the low-tension side of the transformers associated therewith. This has a marked effect on limiting the amount of power that may be developed in the case of a fault and of reducing the duty on the circuit breakers which have to interrupt this fault.

**B. M. Jones:** The remark someone made about the details of the contract for interconnections was brought out very clearly in our company a year or six months ago.

We had a tie with the West Penn Power Company, our neighbor, and six months or so later we tied in with another company. The second tie was purely to carry a block of load, the plan being for one company to shift the load to the other company and not actually to tie in.

After the tie was made we found it would be advantageous actually to operate tied in together. It quickly developed that the second company we tied to was being penalized very severely due to the energy that flowed through its system to the next system and circulated back, a triangle of interconnection, and it involved such an amount of money that we couldn't tie together. We had actually to transfer the load.

When we first went into this second contract nobody had any idea that it would be worth while to tie together, and it just brings out the fact that the details of the contract must be watched very closely and all possible conditions anticipated.

**E. C. Williams:** Considerable comment has been made relative to awkward situations which have arisen due to the lack of coordination between the power contracts and the engineering principles which really dictate the operation of networks. The development of these superpower networks has been so rapid that all of the fundamental characteristics have not been readily recognized. It is the duty of the engineer to appreciate these characteristics and familiarize those people who negotiate these contracts with the importance of such coordination.

The temptation to temporize with the oil-circuit-breaker problem by resorting to breaking up the network into smaller networks and arranging transformers so as to increase the impedance of the circuit, is quite natural. However, the development is still quite young and it may be rather early to start such temporizing. If the development continues at the present rate in a few years we will face the same problems in the smaller pieces of the present network which we now face in the main network itself. It also must be recognized that the breaking up of any network brings with it certain operating disadvantages and interference with the free flow of energy which may affect the division of load between stations and perhaps the cost of production. As in all engineering problems it will no doubt be necessary to effect a compromise but in doing so the engineer should realize the limitations of such compromises and be prepared to take the necessary step in the development when it comes.

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# The Hall High-Speed Recorder

BY E. M. TINGLEY[1]

Associate, A. I. E. E.

*Synopsis.—A new form of oscillograph for recording fault currents and their voltage disturbing effects in electric power systems is described. Representative records are analyzed and further applications of the instrument are suggested.*

### INTRODUCTION

LIFE histories of electrical disturbances in the extensive 60-cycle, 12,000-volt systems of the Commonwealth Edison Company have been written during the last few months by the high-speed recorder developed by Chester I. Hall. The object of this paper is to describe the application of the device and the records obtained with only a limited reference to the details of its construction.

### DESCRIPTION OF RECORDER

This instrument is a form of oscillograph for tracing continuously the maximum values of current and voltage during system fault conditions. Sturdy construction makes it suitable for application in generating stations and substations. It seems to be the only instrument yet developed for this class of service. Its performance lies between that of the standard oscillographs and the switchboard curve-drawing meters with speed-up attachments.

The measuring element or meter is of the saturated magnetic-vane type, having a natural period of vibration sufficiently high to attain full deflection always in the same direction in each half cycle of current measured, and the motion is practically dead beat. The envelop of the maximum deflections is therefore a measure of current or voltage.

Four meters, three for voltage and one for current, are inclosed in a light-tight case, and the records are made on a flat stationary, 11-in. by 14-in., superspeed photographic film.

The optical system consists of an automobile lamp with reflectors and lenses for concentrating light beams on the mirrors of the oscillating systems from which they are reflected to a movable plane mirror, which in turn reflects them to the photographic film. The plane mirror traverses the light beams across the film, giving a time scale to the records of 1 in. per sec. The traversing mirror is operated by a phonograph spring motor through suitable gearing.

A starting relay, dry batteries for the lamp, transformers for the current and voltage meters, and alarm and signal circuits complete the installation.

Under fault conditions, the relay connects the measuring elements to their transformers, lights the lamp, and starts the light-traversing mirror. The starting operations require 1/10 sec. or less. At the end of the record, which continues for 10 sec., the measuring

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[1] Commonwealth Edison Company.

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elements are disconnected from their operating circuits, the lamp is extinguished, and the alarm is sounded.

### APPLICATION

The Hall recorders as applied to the Commonwealth Edison system are installed in generating stations. They are started by fault currents to ground, and they measure this current and the three-phase voltages to ground. As faults invariably go to ground, the maximum information is obtained from a minimum number of recording elements.

The Commonwealth Edison 60-cycle, 12,000-volt system consists of four large separate systems, Crawford, Calumet, Fisk, and Northwest. Each unit system consists of a generating station with radial distribution cables to the substations. The neutral of one generator in each station is grounded through a 3-ohm resistor which limits ground-fault currents to about 2000 amperes. There are several hundred miles of 3-conductor cables in each 12,000-volt distribution system with only a few short overhead or open lines.

The generating stations are usually coupled only through their transformer lines so that a ground fault in one system does not cause ground current in another system. However, Fisk and Crawford are occasionally conductively coupled at 12,000 volts, and with this condition a fault causes neutral current at both generating stations.

The relays were first adjusted to trip with 125-amperes neutral current, but so many transient currents of undiscoverable origin operated the recorders without leaving a record that all the relays were readjusted to trip with 400 amperes. Transient currents were probably caused by synchronizing operations or the starting of transformers or motors.

The rather high condensive coupling to earth by the cables of the distribution systems may possibly be responsible for some of the neutral transients.

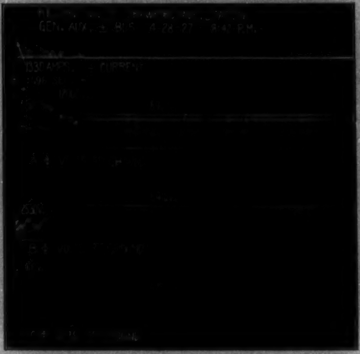
More than 100 records have been obtained, but only a few representative forms can be shown and described. They are necessarily a "behind-the-scenes" view of some of the accidents and failures incident to the operation of a great power system. However, very few of the failures recorded interrupted service.

The following paragraphs describe the faults recorded on the records shown in the corresponding illustrations.

### RECORD NO. 20, CRAWFORD STATION

Lightning on an overhead line started this fault. The *B*-phase was first affected after which the arc extended to the other phases in an irregular manner. The short period of zero neutral current may have been due either to the effect of a three-phase arc or to the momentary complete extinguishment of the arc. The opening of two circuit breakers, indications of which are lost in the arc irregularities, relieved the system of this fault.

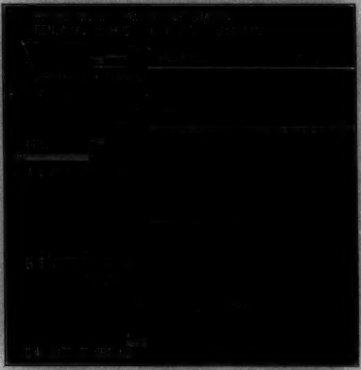
The excessive voltage disturbances shown are with respect to ground only. The delta or phase-to-phase voltage at the generating station is affected only slightly.



The disturbance pattern is characteristic of a long flaming arc in air.

### RECORD NO. 27, CRAWFORD STATION

This is an unusual case of two simultaneous single-phase failures to ground on separate cable lines. One failure by distortion of the system voltage with respect to ground precipitated the second failure and four circuit-breaker openings were required to clear the two



faults. Note that there are seven different steps in the neutral ground current. One of these is probably due to arc variations.

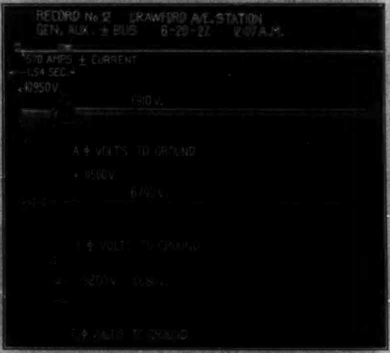
The first failure is on the *A*-phase and the second on *C*-phase. The abrupt increase of current at the beginning of the second fault is characteristic, as practically all records show that cable faults attain high current values very quickly.

The horizontal lines and patterns within the records are due to multiple reflections in the optical system. The vertical bands are caused by slight irregularities in the gears which drive the mirror that traverses the light beams.

A small allowance in the time scale is made for the starting time of the recorder.

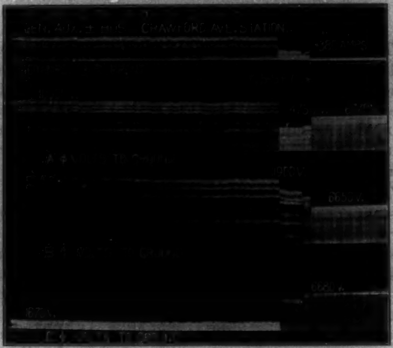
### Record No. 32, Crawford Station

A three-phase cable fault produced this diagram and inspection of the burned cable indicated that the fault probably started between two phase conductors and burned some time before going to ground, as the small time and small ground current indicated by the record do not account for the extent of cable burning. Zero value of neutral current during the first second of the record may be due either to a three-phase arc, or to the entire extinguishment of the arc. The fault was cleared by the operation of two oil circuit breakers, the effects of which are lost in the irregularities of the currents.



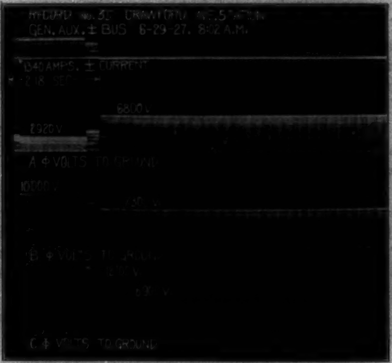
### Record No. 34, Crawford Station

This record started with a *C*-phase cable fault to ground which extended to *A*-phase after 6.71 sec. The circuit-breaker relays were slow to respond to the ground-fault current, but the fault was quickly cleared by three circuit breakers after it developed to include another phase. As there are indicated only two steps in the neutral current reduction and three circuit breakers operated, it seems that two breaker openings were simultaneous.



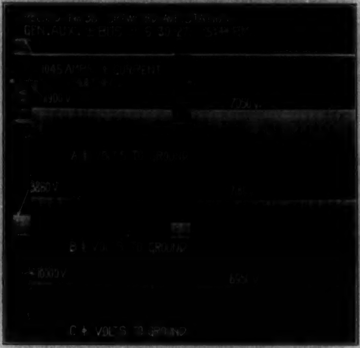
### Record No. 35, Crawford Station

This is a usual fault to ground in one phase of a cable that was relieved by two circuit-breaker openings. The rounded corners in the current cut-off may indicate arcing within the circuit breaker. That the *A*-phase only is involved in the fault is shown by the reduction of the voltage of that phase to ground, and the increase of voltage on the other two-phases. This may be otherwise expressed as the displacement of the neutral point within the delta or as the tendency of the system voltage diagram to stand on one corner.



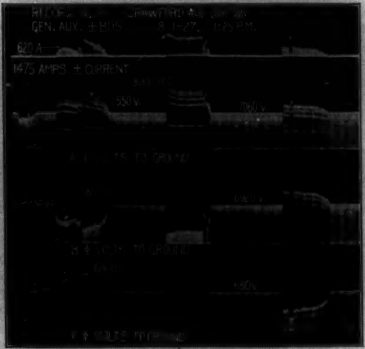
### Record No. 38, Crawford Station

This record was made when system voltage was applied to a faulty cable. It is usual to make a ground test on a faulty cable by applying full system voltage on each phase singly by closing the disconnect and then closing the oil circuit breaker. In this case, the circuit. breaker was closed twice on the faulty phase, *B*, possibly through the defective action of the circuit breaker. Uniform closing and opening speeds in the circuit breaker are indicated in both cases. This is an example of the way in which the Hall recorders furnish checks on the condition of apparatus and on its correct operation.



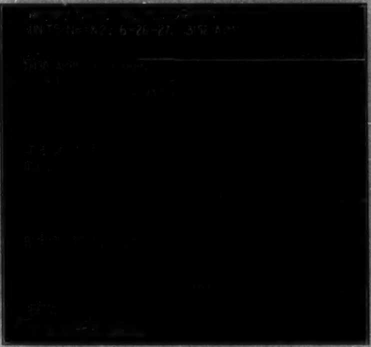
### Record No. 43, Crawford Station

This trouble was caused by the leakage of brine on transformer bushings in an ice plant. Four bushings broke down. Two circuit-breaker operations were required to relieve this fault which may have extended beyond the 10-sec. limit of the recorder. The fault seems to have started with small arcs on all three-phases and then ceased entirely, after which it concentrated on the *B*-phase and then on the *C*-phase. The irregularities in current and voltage are those of long arcs in air.



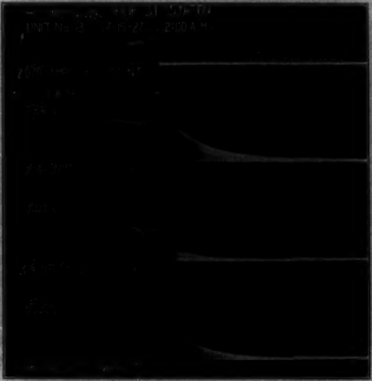
### Record No. 13, Calumet Station

The steady current effect of the single-phase fault in the cable is again shown. The first and greatest reduction of fault current is caused by the opening of the circuit breaker at the generating station and the final interruption is at the substation end of the cable. The fault current burned one cable conductor entirely in two. Small oscillations on *B*-phase voltage indicate that some synchronous apparatus may have been disturbed at the time the first breaker opened.



### Record No. 19, Fisk Station

This most remarkable record of the series shows two cable failures and a generator winding failure, all to ground. In addition, there are three oil circuit breaker operations and the opening of the generator-field circuit breaker, and the resultant dying down of the generator voltage. In this particular installation, the voltage is measured to the generator neutral and not to ground;



consequently, the voltage distortion registered is small.

It is possible to determine the time sequence of only a few of the events. The record started with a high neutral current due to *B*-phase cable fault, as the voltage on this phase is low. After about three seconds the *C*-phase was involved. The resulting voltage disturbance caused the generator winding to break down, which was quickly cleared through the action of the balanced differential relays. The relays also opened the generator-field circuit breaker and the generator voltage died down. The fault persisted on the *B*- and *C*-phases of the generator as indicated by the low voltage on these phases, and the higher voltage on the *A*-phase.

### STARTING CHARACTERISTICS

In the generating stations as the recorders are started by neutral ground currents, a fault between phases does not start the recorder until shortly after it develops into a ground fault. Important parts of some faults are therefore lost. It has seemed impracticable to arrange a relay for starting on excess phase currents, as ground-fault currents are usually small and become lost in the load currents. Also, it is impracticable to start a recorder in generating stations by phase voltage reduction, as this is usually small. Starting on neutral ground current is the best compromise that can be effected.

It has been proposed to install recorders in some substations where the effects of voltage disturbances are important. A quick start may be made here on voltage reduction between phases, where it is important, but there will be no response to phase-to-ground distortions such as are measured at the generators. More complete information will be obtained through two sets of records, one at the generating station and one at the substation.

Records are frequently lost through the improper handling of the film holders and two separate sources of records furnish a good insurance against complete loss in important cases.

### USE IN TESTING

Recently during oil circuit breaker testing, the recorders were found very valuable in measuring effects of the test currents on the system. The long time scale allowed the starting of the instruments through telephone orders just before the test currents were applied. There were, therefore, no lost intervals such as occur in automatic starting. Both generator and substation voltage disturbances were accurately measured. Such information is very valuable where synchronous apparatus or induction motors having no-voltage releases are liable to be shaken off the system due to momentary voltage reductions because of testing or fault currents.

### GENERAL COMMENTS REGARDING RECORDS

Records are not used to locate or identify system faults. This is better done by methods that were used before the recorders were available. Faults are located, inspected, and repaired long before the films are collected and developed. Usually there is a good agreement between the Hall records and inspection reports regarding the phases affected and other details so far as they may be interpreted. Normal faults to ground in cables and resulting breaker operations are rather uniform in performance. Departure from a normal characteristic calls for explanation regarding circuit-breaker relay operation, and in this way the records are of great value in checking the operating condition of such apparatus.

The effectiveness of the isolated-phase principle in generator station design has been fully demonstrated and recorded. On one occasion a single-phase arc to ground on the Crawford bus burned for 2¼ min. without affecting service. The first four seconds of fault produced a record at Fisk Street through a temporary 12,000-volt tie. The remainder was obtained from the speed-up charts.

## Discussion

**C. I. Hall:** The figure in this paper "Record No. 43, Crawford Ave. Station," is one of the most interesting records. It shows such extreme changes of energy conditions that it must be quite obvious that such variations will set up high-speed transients and cause real difficulty in a central-station system.

Mr. Tingley indicated one factor which is of great interest, namely, the total time lag of the relay to get into complete operation after the occurrence of a fault.

The starting operation really consists of two parts: first, the operation of the high-speed relay, and, second, illumination of the light source. The time lag of the high-speed relay, of course, varies with the percentage of load above the critical value for which it is set. These loads vary but in the average case we have found that they are in the order of 500 to 1000 per cent of the setting of the critical value of the high-speed relay. At 500 per cent load on a 60-cycle system it requires 1.5 cycles to get the mechanism connected to the line. Then the time lag of the optical system is 2 cycles. This gives a total of 3.5 cycles. At 2000 per cent load the total time is about 2.3 cycles.

This device in constructed in other forms to meet special conditions. In one form the film moves upon the occurrence of the first short circuit for 10 sec. and then stops provided the short circuit has been opened, but is in condition to restart the instant another fault occurs, and so on, for a total of four. On the other hand, if the fault continues over the period of 10 sec., then the record will continue and give a total of 50 or 60 sec. of record.

Other forms have been constructed in which the chart is stationary, giving merely maximum values.

**B. G. Jamieson:** This materialization of a device which tells of these transient or semi-transient conditions characterized as faults is of the highest order of importance because it provides a medium for an inner discernment of the mechanism of cable breakdowns at least during the period between their inception and their retirement from the system.

The point I want to make has not been stressed this morning, and is the real point of reference in which our interest is centered. We have said, and Mr. Hall has just said very cautiously, that we needn't expect, or we are not justified in expecting a device which anticipates a fault. Perhaps we don't need it. But we should like to know what happens from the instant (if that word applies) of the development of the fault. I think Mr. Hall really knows how that could be accomplished; that is, how the time lag of the device, which was not emphasized but which is very vital in the operation of this instrument, can be controlled. Whether he does or not, it seems to me that the great value of this device as now constructed lies in the fact that it shows not only the data the author gave, but it shows the impotence of relay systems of the conventional order which are unable to function during the fault inceptions, considering the responsibility that is centered upon them in the development of our interconnected systems.

The idea of having a fault developed and prolonged for from eight to ten sec. with all protective apparatus absolutely helpless, taking no cognizance of it, seems almost ridiculous. It isn't that we want to anticipate the fault, but what we want is action in that incipient period and before fault current reaches a magnitude and a rate of propagation that is beyond the power of interrupting devices built or that can be built to cope with it.

What we need is a relay which will take cognizance of that fault in its incipiency. Our problem will be intensified by the prospect of oil-filled cables. If we are going to have oil-filled cables and we attempt to handle faults in this incipient period, I don't know how we are going to find the faults after we retire the cable. Perhaps someone can tell us that, but in any event it must be apparent that we now have within our grasp a device that enables us to concentrate on that important function of retirement of a faulty member before conventional types of relays wake up to the fact that there is trouble.

**F. C. Hanker:** The need of recording equipment that would function during transient disturbances on a power system has long been recognized. Operating companies have been badly handicapped by the lack of information regarding the sequence of disturbances, the values of power surges, the voltage and current conditions during faults that has made it impossible for the engineers to analyze conditions and apply remedial measures to prevent a recurrence of similar difficulties. It is encouraging to find a number of systems are equipping important stations with oscillograph equipment that will furnish records of transients occurring during normal operating conditions.

Mr. Tingley has outlined his experience with one type of recorder and shown the value to the operating company of this sort of record. I cannot let his statement that this is the only instrument yet developed for this class of service go unchallenged.

There has been installed on the system of the Southern California Edison Company a number of automatic recording instruments for over two years. These include 3-element oscillographs, single-element oscillographs, or osisos, special reflecting-type high-speed average wattmeters both single and polyphase, and high-speed dynamometer-type graphic meters. A report of the results from these devices was presented before the Pacific Coast Convention, A. I. E. E., held at Del Monte in September, 1927.

When it is recognized that these instruments have been in service under the control of the operating organization for a period in excess of two years and that during that time not a single oscillograph element has been burned out, we feel we are amply justified in maintaining that this class of equipment is sufficiently rugged for practical operating conditions. I feel that a considerable amount of prejudice to the use of oscillograph equipment was due to the early experience with the original instruments using an arc lamp as the illuminant. I can well recall personal experience with such equipment in the field where practically laboratory experience was necessary to secure satisfactory records.

These conditions, however, have been changed as a result of the development of the portable type of oscillograph with improved galvanometers and incandescent lamps as the illuminant. This development has made the automatic use of this instrument possible.

The analytical studies on power system operation initiated by the Westinghouse engineers in 1921 led to a number of shop and field tests. It was early recognized that records of power surges were absolutely essential to give us the fundamental data necessary in our analytical studies. This led to the attempt to obtain records by modifying existing types of graphical instruments. The natural period of the electro-mechanical oscillations of the ordinary power system varies from ½ sec. to 1½ sec. depending on the size of the system and conditions of load so that it was felt that satisfactory results could be secured by improving existing types of equipment. We were able to obtain time constants of approximately 1/10 sec. with these modified devices but at the expense of a very considerable input to the coils.

It may be of interest to review the progress of the development of these devices as the need for them was indicated during the various field tests that were made to investigate the operation of power systems.

In the first series of tests made on the Pacific Gas & Electric system in May, 1924, an attempt was made to obtain information on the power oscillations by carrying static tests to the limit and recording the readings of the ordinary meters that were available. In addition oscillograph records were taken of current and voltage conditions. The second series of tests was made in January, 1925, during which records were taken of staged short circuits. Oscillograph records of current and voltage were taken and in addition the experimental dynamometer-type graphic meter previously mentioned was used. In an effort to analyze the power surges the oscillograph records were enlarged on a screen and the energy oscillations calculated. It was found in this analysis that the application of the usual form factor to current and voltage waves did not check with the analytical work by some 30 per cent. This led to a further study of the records and it was found that the wave distortions of current and voltage during the transient period were so great that it was necessary to integrate the actual wave forms to get reasonable comparisons between test and calculated results.

The next step in the development of recording equipment was during the tests made on the same system in June, 1925, where reflecting type average wattmeters both single phase and polyphase, having time constants of 1/20 sec. were used. By the use of the optical system considerably greater magnification of angular deflection could be obtained so that usable records with permissible volt-ampere burden were possible.

It was following these tests that the recording equipment was installed on the system of the Southern California Edison Company for the purpose of securing records during actual operation. The staged tests made on the system of the Pacific Gas and Electric Company gave very important data that was extremely useful in substantiating the analytical work previously carried on. It was recognized, however, that it would be desirable to obtain records under actual operating conditions on a system and it was for this purpose that the installations on the more important generating and substations of the Edison Company were made. The results of two years' experience were presented before the Institute in September, 1927, as mentioned previously, and the value of this type of apparatus as an aid in analyzing system operation is evident by the installation of 9-element oscillographs arranged for automatic operation in the new Long Beach generating station. It is also the intention to install similar equipment at the new high-tension substation under construction.

In the last series of field tests made on the Pacific Gas system in June, 1926, a still further development in watt-oscillographs was used. This was the single-phase instantaneous type galvanometer using the bi-filar element for voltage and substituting an electromagnet wound for current for the permanent magnet. These devices have been used in numerous other field tests and have proved their value. Using the standard suspension these elements have a natural period of 4000 cycles per sec. so that they are of sufficient sensitivity to record the more important harmonics that might affect the results. It was recognized that the polyphase element of this type was desirable during the transients in order that the polyphase oscillations could be recorded. Under unsymmetrical short circuits without using any sequence network the record of the single-phase element could not be utilized directly. This difficulty is overcome by the development of the polyphase instantaneous element.

The use of the oscillographic type of equipment enabled us to record accurately the results even with greatly distorted wave forms that occur during transient operation.

In conclusion I feel that the operating companies should cooperate to a greater extent in the installation of recording devices as information of this character is necessary for the engineers to analyze fully the operation of the larger and more complicated power systems. We have been able to operate satisfactorily in the past where systems were comparatively simple and the requirements for continuity of operation were not so rigid. With the great extensions of the interconnections and the increasing size of systems it is necessary to make every effort to keep down the plant investment so that a reasonable return on the capital is possible. This makes it necessary to operate the facilities at more nearly their limits so that it is much more important to know just what these limitations are in order to determine the factors of safety that are permissible. The conditions now existing in the Great Lake region where you have great concentration of power in such a small area will soon spread to other parts of the country, making it of increasing importance to have a fuller understanding of the operation of a system under fault conditions.

**Herman Halperin:** In connection with Mr. Jamieson's discussion of a device in combination with a switch to cause the switch to disconnect faulty apparatus before the failure current becomes too large, which, I presume, would be at least a few hundred amperes, he stated that there might be considerable difficulty in locating the failure in an oil-filled cable when only such a small fault current was allowed to flow.

Experience with testing 132-kv. oil-filled cables in our laboratory indicates that there should be no great trouble in locating such faults. In an accelerated life test on oil-filled cable a failure occurred in the cable but did not burn a hold through the sheath. It is estimated that the failure current (furnished by the testing transformer) was only 35 amperes and that it flowed for 0.3 sec.

In order to reduce suitably the fault for location, it was necessary to go up to only 185 kv. with a d-c. kenotron cable-testing outfit at Northwest Station. The reducing current used was only 0.2 ampere. This outfit, however, is rated at 400 kv. and may be reconnected to supply 2 amperes at 50 kv. For field conditions, where the fault would cause a hole through the sheath of the cable, oil would flow through the fault out of the cable. For such conditions it may be necessary for final fault reduction also to use a d-c. supply of 1000 to 9000 volts and with a current capacity of 6 to 15 amperes to carbonize properly the fault in order that it may be readily located by the ordinary methods. Nevertheless, it does not appear that there will be any great difficulty in the location of such failures.

# The Application of Relays for the Protection of Power System Interconnections

BY L. N. CRICHTON[1] and H. C. GRAVES, Jr.[1]

Member, A. I. E. E. Associate, A. I. E. E.

***Synopsis.****—This paper is a compilation of many of the new methods for relay protection required by superpower interconnections. The ideas have been obtained from various sources and represent good present day practise. The general requirements for such interconnections are mentioned with particular reference to protection against phase-to-phase short circuits in those cases where the short-circuit current, under certain system conditions, is less than the full-load current under other conditions. The clearing of accidental grounds is discussed and a new study of residual currents on systems of different types is given. This study indicates the usefulness of certain inverse time limit relays on systems having dead grounded power transformer neutrals at all switching stations. Bus protection and "back-up" methods are described.*

*Some of the new relays which have been developed, or improvements which have been made to older types in order that the new demands may be met, are described; and there is illustrated a typical relay installation similar to that now being placed in service on a 220-kv. interconnection.*

* * * * *

THE interconnection of large power systems requires special treatment of its protective relay installation in order to secure proper automatic sectionalizing. This is particularly true of extra high-voltage interconnections which have their transformer neutrals grounded at all stations. Such systems are not numerous, but they are important and their number is increasing. In any such relay installation it is important to adopt protective methods which not only are suitable for the immediate requirement but which will be applicable to future revisions and extensions. Interconnections between large power units impose more strenuous demands on the relay protective equipment than do individual systems, even those of a large size. The problem is different and in some ways more difficult.

## RELAY REQUIREMENTS

The most important requirement is that all faults be cleared quickly. This prevents unnecessary burning of conductors and equipment, but primarily, such quick clearance will minimize the possibility of the system becoming unstable. Therefore the securing of discrimination by means of time limit relays is not desirable although it may sometimes be necessary or convenient.

The complete installation must allow flexibility of system operation. Perfect protection should be possible when any line or piece of equipment is cut out of service and, what is more difficult, protection should be obtained without change in relay adjustment when a large unit of power is entirely removed.

The initial relay installation should permit unlimited extension and revision of the power system.

It should operate satisfactorily on the lines forming the interconnection between the systems without requiring too great a change in the relay protection already installed on the individual systems which are being united.

It must protect against "bus faults." High-voltage switching stations have become so elaborate that the possibility of trouble on the bus bars or on the station equipment is as great as that of a number of miles of transmission lines.

It must provide "back-up" protection; by this is meant that trouble should be cleared from the system, possibly with some little delay, even though the circuit breaker which would ordinarily clear such trouble should fail to operate. Some types of relays will operate in this manner by means of their inherent characteristics, but other types require the use of additional relays. For simplicity it is desirable that protection against bus faults and back-up protection be obtained by the same means, thus making unnecessary the use of complicated differential schemes commonly used for bus protection.

It is desirable to eliminate the use of high-voltage potential transformers so far as possible, not only because of their expense, but also because of the hazard which they, themselves, introduce in the system.

Economy in the relay system is desirable, but because high-voltage lines and equipment are inherently expensive, if such a procedure results in eliminating more expensive high-voltage equipment the best over-all economy may be obtained by adopting an expensive relay system.

*Types of Relays Considered.* In order to satisfy the needs of recent interconnections, a number of new methods of using the conventional types of relays have been developed and entirely new relays have been designed; namely:

For protection against short circuits,

1. Low-current range impedance relay (type *C Z*).
2. Fault detecting over-current and undervoltage relays.

For protection against grounds,

3. Definite time, directional relay with phase compensation in the potential circuit (type *C R*):

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[1] Both of the Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

*Presented at the Regional Meeting of District No. 5 of the A. I. E. E., Chicago, Ill., Nov. 28-30, 1927.*

4. Definite time, current directional relay (type *G R C*).
5. Inverse time, current directional relay (type *C W C*).
6. Inverse time, directional relay with phase compensation in the potential circuit. (type C W).

The use of these new methods and devices will be described herein with only brief references to methods which are already in common use.

## Protection Against Phase-to-Phase Faults

*General Conditions.* The nature of a high-voltage interconnection system is such as to make difficult any application of relay equipment which will satisfy the demands previously enumerated. The purpose of an interconnection is usually to permit the exchange of power, and any number of causes may necessitate periodic changes in location of connected generating capacity. These changes may occur daily due to load conditions, or seasonally due to change in available generating capacity. This results in a change in magnitude of fault current, due not only to the variation in total connected generating capacity, but also to the change in location of this capacity. Thus, at some points on the system, it is quite conceivable that fault currents which should cause relay operation may be smaller under some conditions than the maximum load current under other conditions.

The interconnecting system is usually composed of long high-voltage transmission lines capable of transmitting relatively large blocks of power. The high load capacity of these lines reduces the number of parallel lines necessary, thus making protection difficult. Also, the expense of substations or switching stations is high and their number is therefore correspondingly reduced. To reduce expense, the system may adopt the form of a triangle, or loop, only one of a pair of lines may be carried through a substation, or different routes may be followed by the various lines. In addition to these difficulties, later extensions invariably tend to complicate relay protection.

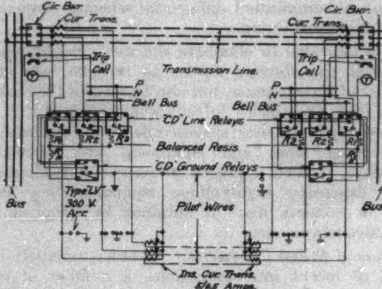


FIG. 1—BALANCED-CURRENT PILOT-WIRE SCHEME USING SELECTIVE DIFFERENTIAL RELAYS

*Pilot Wire Protection.* To clear faults in the minimum time, theoretically, the best solution probably lies in the use of differential bus protection and pilot wire line protection. Fig. 1 illustrates a pilot wire scheme which has several advantages. This is a circulating current scheme and the burden imposed on the current transformers is quite low. In this method, open circuits on pilot wires put the relay in an operative condition for faults either external or internal to the section. This scheme is novel, in that four balancing resistors are used instead of three, with the result that balanced conditions are maintained irrespective of whether a through fault is phase-to-phase or phase-to-ground. This permits the use of ground relays having a low-current setting, thus increasing the sensitivity of the protection. However, for applications where ground fault protection is not desired, the ground relays (but not the balancing resistors, $R_n$), may be omitted. If the ten-to-one ratio insulating current transformers be used, this protection may be applied to lines of great length because of the effective low impedance of the pilot wires. For shorter lines, where the pilot wire impedance is low, the insulating current transformers may be omitted unless they are required for protection against high voltages. With insulating current transformers of the ratio shown, the balancing resistors $R_1$, $R_2$, and $R_3$ should each be equal to 1/200 of $Z$, the pilot wire impedance, plus the impedance of the insulating current transformers; but the neutral balancing resistor, $R_n$, should be equal to 1/200 $Z$ only.

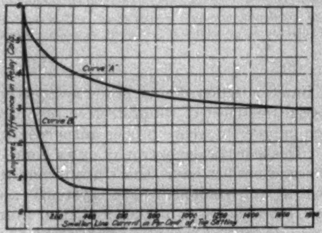


FIG. 2—TRIPPING-CURRENT CHARACTERISTICS FOR SELECTIVE DIFFERENTIAL RELAYS

Relay No. 1 Fig. 3 operates on Curve A
Relay No. 2 Fig. 3 operates on Curve B
Relay set on 3-ampere tap

The characteristics of the type *C D* selective differential relay as shown in Fig. 2 are quite suited to this application. Its design is such that, with a fault in a section protected by this pilot wire scheme, the breaker through which the maximum current is flowing will operate on curve *A* and that through which the minimum current is flowing will operate on curve *B*. As a result, that breaker which has the least tendency to trip is operating on the most sensitive characteristic of the relay.

Although the pilot wire scheme of protection approaches very closely the ideal, the difficulty of installing and maintaining pilot wires prevents its use on all but the shortest transmission lines. The periodic tests, which are essential to all protective equipment, are rather intricate on this scheme. Another objection to this scheme is found in that additional relays must be installed for back-up protection.

*Carrier Current Protection.* In order to overcome the disadvantages of using pilot wires, effort has been made to use the transmission lines as pilot wires by superimposing on them high-frequency potentials or currents, as is customary for carrier-current telephony. The advantages of this scheme over the pilot wire scheme lies in the fact that no additional wires are necessary. For protecting transmission lines by means of superimposed high frequency there are two general methods which correspond fairly well with the standard pilot wire scheme. In one scheme, radio frequency currents are used, produced by a separate generator at each end of each section of line. The generator is connected to the current transformer on the power line in such a way that the emission of impulses is controlled by the direction and amount of the line current. Reception of the impulses at the other end of the line is controlled by the current transformer at that end and the complete arrangements are such that the radio relays will permit the breakers at each end of a line to be tripped whenever the power current flows into the section from both ends. The actual tripping is done by over-current or directional relays of the conventional type. In order to keep the high-frequency current in its own section of line a tuned reactor is placed between each power conductor and the bus bars.

Another scheme makes use of a lower frequency, say from 500 to 2000 cycles, generated by several small three-phase generators located at various points on the system, the high-frequency potential being superimposed on the main power supply. This superimposed frequency is high enough so that very little of it will leak through the power apparatus because of its high impedance to the high frequency. When a fault occurs, the nearest high-frequency generators cause a heavy current to flow and operate high-frequency over-current relays at each end of the faulty line. The distant relays will not be operated because the impedance of the system to such high frequencies keeps the current down to a small value. In many cases it is necessary to put a small reactance in each end of a section of line in order to make sure that the current in the good sections will be kept small.

Both of the high-frequency schemes have features which appeal to the protection engineer, and it is quite likely that as experience is gained in their operation, they will become popular.

*Bus Protection.* When either a pilot-wire or a carrier-current scheme is used, some form of bus protection must be applied. Many engineers hesitate about installing differential protection where many bushing-type current transformers must be connected in parallel. Heel-and-toe switches connected in the current transformer leads and operated by the breaker are sometimes used under such conditions, but are generally considered as a hazard and therefore to be avoided if possible.

To overcome these objections and the complex connections of the standard bus differential, protection is often provided against phase-to-ground faults only. One means of doing this is by grounding the tower structure through current transformers. The current transformer secondaries are connected in parallel and operate a relay to clear the bus. It is not necessary that any special precautions be taken to isolate the tower from ground since the relay may be set to operate on only a portion of the total fault current.

This scheme may be amplified so as to isolate portions of the tower structure (electrically) from others, grounding each separately and thus permitting the isolation of only the faulty section of the bus. The insulation required between tower sections for this application need be only for low-voltage, or rather in the nature of high resistance.

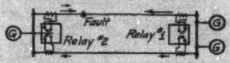


FIG. 3—SINGLE-LINE DIAGRAM SHOWING CURRENT CONNECTIONS OF SELECTIVE DIFFERENTIAL RELAYS FOR PARALLEL LINE PROTECTION

*Parallel Line Protection.* The desirable characteristics of the selective differential relay (as shown in Fig. 2), makes it suitable for protection of parallel lines provided there is a source of feed at each end. When the operating currents through the relay coils are in the same direction, as shown in Fig. 3 by relay No 1, the indications are that the fault is near the other end of the line and the relay operates on the least sensitive characteristic, as shown in curve *A* of Fig. 2. When the currents through the relays are in opposite directions, as indicated by relay No. 2 in Fig. 3, the indications are that the fault is close to that particular relay. This relay then operates on the sensitive characteristic shown in curve *B*, thus permitting of the relay being installed at stations where only a small amount of feed-back is available. If the relay operation is not simultaneous, the opening of a breaker by one set of relays then permits the other set of relays to operate on the more sensitive characteristic curve.

During conditions of single-line operation, the differential relay is usually inoperative, and some form of back-up relay is essential. The application of differential relays is therefore usually made in conjunction with back-up over-current or directional over-current relays, the differential relays being inoperative during conditions of single-line operation. The back-up relays also furnish protection against bus faults. Therefore, balanced protection on parallel feeders approaches the protection afforded by pilot wires during conditions of parallel operation, but for faults within the section during single-line operating conditions a long time is required for clearing, since selective settings are then used.

Under many operating conditions, a substation may have a connected source of feed-back into a fault, so that directional back-up protection is necessary during conditions of single-line operation. For this application, cross-connected, over-current, directional relays are applicable. This scheme is shown in Fig. 4A. The relays each consist of a directional element and an over-current element, the contacts of the two elements being connected in series. The common points of these two sets of contacts is brought out of the relay case by a separate stud. The directional elements in both sets are practically instantaneous. The over-current element in one set of relays is given a short-time, low-current setting, and the over-current element in the other set is given a long-time, high-current setting.

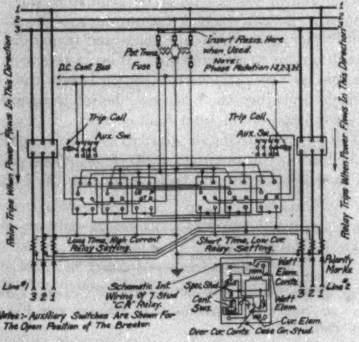

1
2
3
1
2
3
Insert Resis. Here when Used
Pot Trans.
Fuse
Note:
Phase Rotation 1-2, 2-3, 3-1
D.C. Cont. Bus
Relay Trips When Power Flows In This Direction
Relay Trips When Power Flows In This Direction
Trip Coil
Aux. Sw.
Trip Coil
Aux. Sw.
Long Time, High Current Relay Setting.
Short Time, Low Cur. Relay Setting.
Watt Elem. Conts.
Polarity Marks
Line #1
3 2 1
Line #2
3 2 1
Schematic Int. Wiring Of 7 Stud "CR" Relay.
Spec. Stud
Cont. Sws.
Watt Elem.
Cur. Elem.
Over Cur. Conts.
Case Gn. Stud.
Notes:- Auxiliary Switches Are Shown For The Open Position of The Breaker.

FIG. 4A—PROTECTION FOR A PAIR OF PARALLEL LINES

**Effective for both parallel and single-line operation, using directional over-current relays**

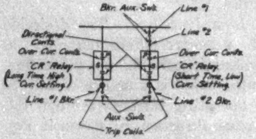

Bkr. Aux. Swk.
Line #1
Line #2
Directional Conts.
Over Cur. Conts.
"CR" Relay
(Long Time High Cur. Setting.)
Over Cur. Conts.
"CR" Relay
(Short Time, Low Cur. Setting.)
Line #1 Bkr.
Line #2 Bkr.
Aux. Swk.
Trip Coils

FIG. 4B—SCHEMATIC DIAGRAM OF TRIP CIRCUITS OF FIG. 4A

Fig. 4B shows the schematic diagram of the trip circuits. The common studs on the two sets of relays are tied together for each individual phase so that, from this common connection, each directional element may trip its individual breaker. During conditions of parallel-line operation, the closing of either set of over-current contacts will cause the tripping of one or the other breaker, depending upon which directional element is closed. The disconnection of one line or the other, producing the conditions of single-line operation, causes the low-current short-time over-current elements to be disconnected from the circuit so that tripping must be performed by the relay having the high-time setting. These high-time over-current relays are set so as not to operate under conditions of maximum load current, and also to give the proper selective setting.

The objections to the use of balanced protection lie in the fact that the relays which give quick clearing of faults afford no back-up or bus protection, and extra relays must be used for this purpose. Also, under conditions of single-line operation, long-time is required for clearing a fault on the line remaining in service. The cross-connections are relatively complicated, and testing and checking is made more difficult. In addition to these objections, the cross-connected directional relay protective scheme requires a source of potential. This objection, however, is not serious, since a suitable low-voltage set of potential transformer is nearly always available and the secondary potentials from these potential transformers may be used.

*Impedance Relays.* The application of impedance relays satisfies many of the demands placed on protective equipment for interconnections. Particularly is it true that rendering the system more complex does not necessitate increased time for operation, nor does the relay place limitations on the permissible system connections. The time required for clearing faults does not become cumulative. Bus protection, quick clearing of faults, and single-line protection are all secured.

Used on transmission lines, irrespective of whether parallel lines or single lines are in service, the impedance relay will clear faults as quickly as will balanced relays, when faults are located near the extremities of the line. With a fault in the center of the section, the impedance relays will clear in approximately four-tenths of a second; and balanced relays, under the best operating conditions, may clear these faults faster than will the impedance relay. On the other hand, the impedance relay operates effectively irrespective of whether one or two lines are connected in parallel and is independent of other changes in operating conditions.

Fig. 5 shows a typical connection of impedance relays. When applied in this manner, the relays protect against phase-to-phase faults only and constitute only a small measure of protection against phase-to-ground faults. The use of potential is required with the impedance relay, but this objection may be overcome, as previously mentioned, by using low-voltage potential transformers. Another method of obtaining correct potential for relays when high-voltage potential transformers are not available is covered later.

*Relay Operation with Low Current Faults.* To meet fully the requirements of relay equipment applicable to interconnections, the relays must operate on fault currents, which may be less than full load current. In order to satisfy this demand, a fault-detecting device has been developed,—a device composed of an undervoltage and an over-current element connected in each phase. The contacts of these elements (two per phase or a total of six) are connected in parallel, so that any conditions of either undervoltage or over-current will cause the relay contacts to be closed. In applying this device, the over-current element is set to operate at a current value corresponding to approximately 125 per cent of the maximum load which is expected in practise. Therefore, the current relays should never operate unless heavy fault currents are flowing. The undervoltage device is set for, say, 75 per cent of normal voltage.

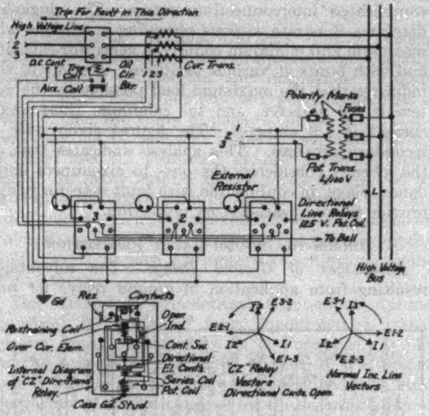

Trip For Fault in This Direction
High Voltage Line
1
2
3
D.C. Cont.
Trip Coil
Aux. Coil
Oil Cir. Bkr.
1 2 3
0
Cur. Trans.
Polarity Marks
Fuses
1
2
3
Pot. Trans. 1/100 V
External Resistor
L
3
2
1
Directional Line Relays 125 V. Pot. Coil.
To Bell
High Voltage Bus
Gd.
Res.
Contacts
Restraining Coil
Over Cur. Elem.
Internal Diagram of "CZ" Directional Relay.
Oper. Ind.
Cont. Sw.
Directional El. Conts.
Series Coil
Pot. Coil
Case Gd. Stud
E3-2
I3
E2-1
I2
I1
E1-3
"CZ" Relay Vectors Directional Conts. Open.
E3-1
I3
E1-2
I2
I1
E2-3
Normal Ind. Line Vectors

Fig. 5—Typical Connection Diagram of Impedance Relays Applied to Sectionalize Wire-to-Wire Faults on Transmission Sections

The principle of operation of this combination is quite simple. If the distribution of generating capacity is such that the bus voltage will not drop below approximately 75 per cent of normal, the current to a fault near the bus must necessarily be high. On the other hand, if the magnitude and distribution of the generating capacity is such as to permit only a small current to flow to the fault, the bus voltages near this fault must necessarily be very low. As a result, either the over-current or the undervoltage relay is sure to operate with a fault so located as to demand their operation for proper clearing. In order to fully meet the various conditions existing in practise, both the over-current and the undervoltage relays have a suitable range of adjustment.

These relays are used in conjunction with standard low current relays in such a manner as to render the protective relays inoperative until a fault occurs. The fault detector relays may be used in conjunction with directional relays connected as shown in Fig. 4A to guard against the following two conditions, which are likely to cause faulty operation on interconnections.

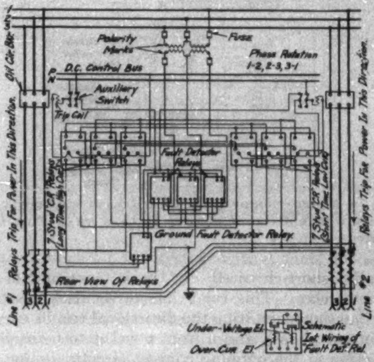

1
2
3
Oil Cir. Bkr.
Polarity Marks
Fuse
Phase Relation 1-2, 2-3, 3-1
P
N
D.C. Control Bus
Auxiliary Switch
Trip Coil
Fault Detector Relays
Relays Trip For Power In This Direction.
7 Stud "CR" Relays Long Time High Cur.
7 Stud "CR" Relays Short Time Low Cur.
Relays Trip For Power In This Direction.
Ground Fault Detector Relay.
Rear View Of Relays
Line #1
3 2 1
3 2 1
Line #2
Under-Voltage El.
Over-Cur. El.
Schematic Int. Wiring of "Fault Det." Rel.

Fig. 6A—Protective Scheme for a Pair of Parallel Lines when Fault Current May be Less Than Load Currents

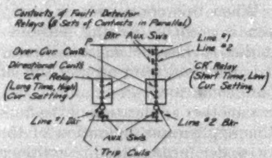

Contacts of Fault Detector Relays (6 Sets of Contacts in Parallel)
Bkr Aux Sws
P
Line #1
Line #2
Over Cur. Conts
Directional Conts
"CR" Relay (Long Time, High Cur Setting)
"CR" Relay (Short Time, Low Cur Setting)
Line #1 Bkr
Line #2 Bkr
Aux Sws
Trip Coils

Fig. 6B—Schematic Diagram of Trip Circuits of Fig. 6A

The first of these conditions occurs only when the low-set relays have current settings for less than full load. The faulty operation is caused when an operator at a receiving substation trips one of the breakers on a pair of parallel lines carrying nearly full-load current. This causes all current to flow over one line and this line will be tripped at the sending end by the low-set relays. To correct this trouble, fault detector devices may be applied as shown in Fig. 6. As shown in the schematic diagram, Fig. 6B, the contacts of fault detector relays are so connected as not to permit the low-setting over-current contacts to cause tripping unless a fault occurs on the system. The low-setting relays may therefore be given a current setting of any value without danger of tripping due to this operating condition.

The second condition occurs when it is necessary to set both the short-time and long-time relays to operate under less than full-load conditions. The connections are then changed so that the current elements of both the long-time and short-time directional relays are normally short-circuited by back contacts of an auxiliary relay. This relay has three back contacts (each one short-circuiting the directional relay's current coils in one phase), and a front contact to be used for connecting in the tripping contact circuits, or for bell alarm, as may prove desirable. This auxiliary relay is normally deenergized and is energized when any of the fault detector relays close contacts due to fault conditions. When this connection is used, the relays may be given a sensitive setting without danger of tripping out due to heavy load conditions, since the short circuit is removed from around the current coils only under fault conditions.

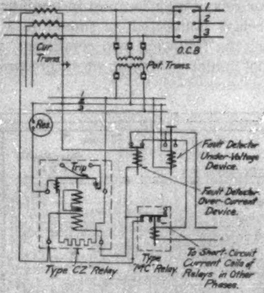

1
2
3
O.C.B
Cur. Trans.
Pot. Trans.
Res.
Trip
Fault Detector Under-Voltage Device.
Fault Detector Over-Current Device.
Type 'CZ' Relay
Type 'MC' Relay
To Short-Circuit Current Coils of Relays in Other Phases.

FIG. 7—APPLICATION OF IMPEDANCE RELAYS FOR PROTECTING SYSTEMS WHERE FAULT CURRENT IS LESS THAN FULL-LOAD CURRENT

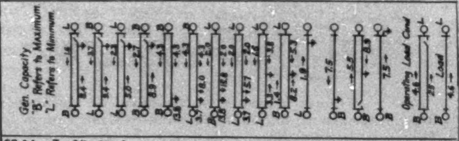
Fig. 7 shows another application of the fault detecting relay. In this application, operation of the line protective relay under heavy load conditions is again prevented because the current coils of the relay are short-circuited. The fault detecting relays, when deenergized, permit the back contacts of the auxiliary relay to short-circuit the line relays. The fault conditions on the system cause the contacts of one or more elements of the fault detector relays to close, thus energizing the auxiliary relay and removing the short circuit from the impedance relay. Then the impedance relay is permitted to function, and will operate, if the impedance between the station bus and the fault is sufficiently low.

Thus, after a fault on the system has occurred, all impedance relays on the system are connected into service, permitting the one nearest the fault to open the circuit breakers on the faulty section. Since the impedance relay current coils are normally short-circuited, they may be set on the one-ampere tap although maximum load currents may be five amperes. This scheme has a second advantage, in that the relay burden is removed from the current transformers except under fault conditions.

Fig. 8 illustrates an actual analysis which was made on a pair of parallel lines constituting a portion of a complicated interconnecting system. The single-line diagrams illustrate various operating conditions with maximum and minimum connected generator capacity, and with faults at various locations. A study of this indicates that the maximum load possible on the system is 4.6 amperes, and the minimum short-circuit current is 1.9 amperes. The figures given refer to secondary amperes. This analysis indicates that, of the schemes considered, the one- to six-ampere impedance relays, in conjunction with fault detector relays, provide the most satisfactory protection.

## PHASE-TO-GROUND FAULT PROTECTION

*Advantages of Ground Relays.* The advantages resulting from application of ground relays for protection of transmission circuits are now well established. These advantages may be briefly itemized as follows:



| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CD 3 Amp. Tap | O.K. | O.K. | ? | O.K. | O.K. | O.K. | O.K. | ? | ? | O.K. | — | — | — | — | O.K. | — |
| CD As O.L. | O.K. | O.K. | ? | O.K. | O.K. | O.K. | O.K. | ? | ? | O.K. | X | O.K. | O.K. | ? | O.K. | O.K. |
| CD 1.5 Amp. Tap | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | — | — | — | — | X | — |
| CO 6 Amp. Long Time | O.K. | O.K. | X | O.K. | O.K. | O.K. | O.K. | X | X | O.K. | X | O.K. | O.K. | ? | O.K. | O.K. |
| CZ Line 4 Amp. | O.K. | O.K. | ? | O.K. | O.K. | O.K. | O.K. | ? | X | O.K. | X | O.K. | O.K. | O.K. | O.K. | O.K. |
| CZ Line 5 Amp. | O.K. | O.K. | X | O.K. | O.K. | O.K. | O.K. | X | X | O.K. | X | O.K. | O.K. | O.K. | O.K. | O.K. |
| CZ Trans. Bank Long Time | X | O.K. | X | X | O.K. | O.K. | O.K. | X | X | X | ? | O.K. | O.K. | O.K. | O.K. | O.K. |
| CR Cross Connection | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | X | O.K. | O.K. | ? | X | O.K. |
| CZ Line 1 Amp. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. | O.K. |

? Relay Operation Doubtful.
X Relays Can not Operate Because of Low Current Fault.
— Relays Can not Operate Because of Open Pallet Switches.

FIG. 8—COMPARISON OF RELAY SCHEMES FOR PROTECTION OF A PAIR OF 220-KV. TRANSMISSION LINES

a. Ground relays operate on residual currents and so may be given a more sensitive setting than can the relays protecting against line-to-line faults.

b. These sensitive settings are necessary because the magnitude of ground currents may be reduced below that value necessary to cause prompt operation of the relays normally protecting against line-to-line faults either by impedance in the neutral connections of the transformer banks by resistance at the point of fault or by the high earth return impedance.

c. A high percentage of faults on transmission line cause ground current to flow. Thus, the residual relay, with its relatively quick timing, increases the speed of clearing a large percentage of the faults.

d. When this relay is used, those protecting against phase-to-phase faults act as a back-up protection.

e. On certain types of system connections, an inverse-time, over-current, residual-current relay may be used and the distribution of ground current is such as to cause the relays closest to the fault to operate always very quickly.

*Distribution of Residual Currents.* On a system where the neutrals of all equipments are solidly grounded, the distribution and magnitude of fault currents differ depending on the type of faults. As a result of this, the study of phase-to-phase fault conditions may not be sufficient to permit accurate setting of relays used for protection against phase-to-ground faults. In many cases a special study is required to determine the distribution of ground current, and this study quite frequently shows that protective equipment which is superior to that available for phase-to-phase fault may be applied for protection against phase-to-ground faults.

The Method of Symmetrical Components (phase sequence) for analyzing fault conditions on transmission lines, developed by C. L. Fortescue,[2] simplifies this otherwise complicated problem. The magnitude of residual currents may be determined with little more effort than that required for the determination of the positive phase sequence quantities corresponding to a three-phase fault. To show the desirability of making this separate study, and to illustrate application of ground relays, a few results of a study of a simple system are given.

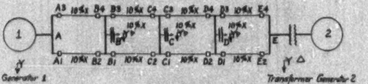


FIG. 9—SYSTEM LAYOUT FOR ILLUSTRATING CURRENT DISTRIBUTION

The system used in these calculations is shown in Fig. 9. At one end of the system a generator is shown connected through a transformer bank, and at the other end of the system a generator is connected directly to the system. This has been done to illustrate that some difference exists depending on whether the generator is connected directly to the system or through a transformer bank. The reactance of both the generator alone, and of the generator in combination feeding through the transformer bank has a total impedance of 15 per cent.

The transformer banks at the substations are in some cases assumed to be connected star-delta with solidly grounded neutrals, so that they have the effect of grounding transformer banks on the system. To illustrate the effect of these banks as compared to delta-connected banks, certain calculations have also been made with the transformer banks disconnected from the substation busses.

Fig. 10 illustrates the distribution of conductor currents throughout the system with a fault located between Stations $B$ and $C$ on phase $A$ conductor of one of these parallel lines. Fig. 11 illustrates the distribution of conductor currents for a similar fault; but here, the substation transformer banks are assumed to be delta-delta connected. $I_A$, $I_B$, and $I_C$ are the phase currents and those marked $I_G$ are the generator and transformer bank neutral currents.

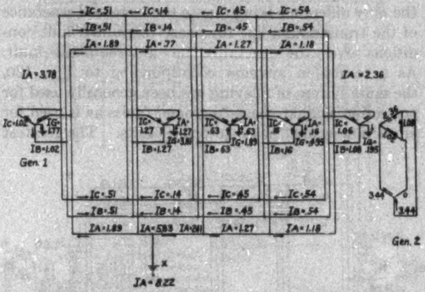


FIG. 10—FAULT-CURRENT DISTRIBUTION DIAGRAM

Showing effect of grounding the neutral of substation power banks

By comparing these two figures, it will be seen that the magnitude and distribution of conductor current is radically changed, depending upon whether the substation transformer bank neutrals are solidly grounded or not. In Fig. 10 the biggest portion of the ground current flows through the neutrals of the substation transformer banks adjacent to the fault. The banks farthest from the fault pass only a small amount of residual current, the magnitude decreasing as the distance to the fault increases. This residual current distribution will vary depending upon the relative impedances of the transformer banks and transmission lines to the flow of zero phase sequence current, and therefore demands special study.

Fig. 12 illustrates the difference in current distribution, depending on the type of faults and type of system. Fig. 12A shows the distribution of current for a three-phase fault. Fig. 12B illustrates the distribution of residual current for a fault located as shown on Fig. 10. The values shown in Fig. 12B are equal to three times the zero-phase sequence current. They are therefore the residual currents which would flow through the relay coils of the ground relays. It is to be noted that here the current in the relays on the faulty section is much greater than that in any other relays on the system. This is true irrespective of whether the lines are connected in parallel or whether one line is disconnected from service. Fig. 12C illustrates the residual current which would flow through the ground relay coils for a fault located as shown on Fig. 11.

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[2] A. I. E. E. TRANS., 1918, Vol. XXXVII, Part 2, p. 1027.

Figs. 12A and 12C resemble each other very closely, the only difference being due to the increased reactance of the transmission line for phase-to-ground fault conditions over the reactance for a three-phase fault. As a result, on systems corresponding to Fig. 12C, the same system of relaying has been generally used for protection against phase-to-ground faults as is used for protection against phase-to-phase faults. The greatest advantage of ground relays may be obtained from the current distribution as shown in Fig. 12B. Here, definite advantages in selectivity, speed of clearing, and sensitivity may be obtained by the use of ground relays. A comparison of Figs. 12A and 12B will illustrate that the use of ground relays with proper characteristics would assist materially in securing suitable relay protection on a system of this type.

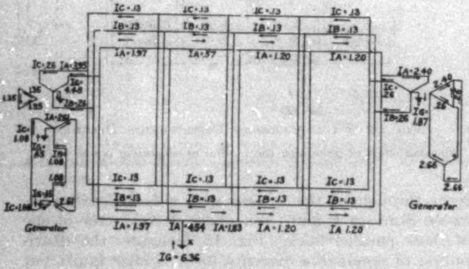
IC = .13
IB = .13
IA = 1.97
IA = .57
IA = 1.20
IC = .26
IA = 3.95
IC = 4.45
IB = .26
1.35
IA = 2.61
IC = 1.08
IG = .45
IB = 1.08
1.08
IB = .45
IC = 1.08
2.61
Generator
IA = 2.40
IC = .26
IB = .26
IG = 1.87
2.40
.26
2.66
2.66
Generator
IA = 4.54
IA = 1.83
IA 1.20
IG = 6.36

FIG. 11—FAULT-CURRENT DISTRIBUTION DIAGRAM

Conditions identical with those shown in Fig. 10 except that substation transformers have been removed. Generator No. 1 has been replaced by an equivalent impedance

*Definite-Time Ground Relays.* Fig. 13 shows a diagram of connections for relays suited to the protection of a system with current distribution similar to that shown in Fig. 12B. This diagram shows selective relays applied as for protection against single-line operation. Standard directional relays are used for protection against phase-to-phase faults. The directional ground relay is of the low energy type with low-current setting. It also differs from the directional relays used for protection against phase-to-phase faults, in that maximum torque is obtained on the directional element of the ground relay when the relay current lags behind the relay potential.

Fig. 14 shows the distribution of residual currents in the system as shown in Fig. 11, except that a fault impedance of 10 per cent resistance is present. The vector diagrams at the various substation busses and at the faults are shown. As may be seen from this, the phase displacement between the residual voltage and the residual current on this system will always be 90 deg. so long as the system impedance is pure reactance.

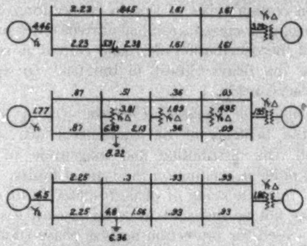
2.23
.845
1.61
1.61
4.46
2.23
.571
2.38
1.61
1.61
.87
.51
.36
.05
1.77
3.81
1.83
4.95
6.89
2.13
.36
.09
1.35
8.22
2.25
.3
.93
.93
4.5
2.25
4.8
1.56
.93
.93
1.86
6.36

FIG. 12—A COMPARISON OF FAULT-CURRENT DISTRIBUTION WITH IDENTICAL FAULT LOCATION

A—Three-phase fault-current distribution
B—Residual-current distribution with grounding transformers on a line-to-ground fault
C—Residual-current distribution without transformer banks on a line-to-ground fault

If this were true for all systems, the theoretically correct relay to use would be one in which the maximum torque is obtained when there is a phase displacement of 90 deg. between voltage and current. On the actual system, resistance is present in the transmission lines and equipment. This will tend to decrease the dis-

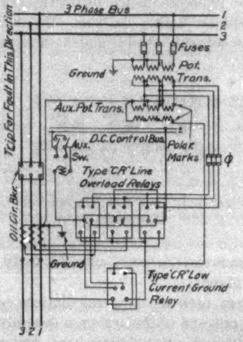
3 Phase Bus
1
2
3
Fuses
Ground
Pot.
Trans.
Aux. Pot. Trans.
Aux.
Sw.
D.C. Control Bus
Polar.
Marks
Φ
Type "CR" Line
Overload Relays
Trip For Fault In This Direction
Oil Cir. Bkr.
Ground
Type "CR" Low
Current Ground
Relay
3 2 1

FIG. 13—DIRECTIONAL LINE AND GROUND PROTECTION FOR ONE THREE-PHASE LINE

placement angle. Under conditions where the phase-to-ground fault has no resistance and the neutrals of the transformer banks or generators are grounded through a high resistance, it is theoretically possible for the residual current and the residual voltage to be in phase, so that the unity power factor condition should cause the maximum torque. It is therefore desirable that this type of relay should secure the maximum torque at some angle lying in between zero and 90 deg. so as to be applicable to any system conditions. Until recently, relays commonly used for this purpose have had approximately true watt characteristics, and it was possible for these relays to operate improperly under certain fault conditions. Where such a relay is now in use, it may be desirable to insert a phase shifting device in its potential circuit so as to obtain the proper phase relation.

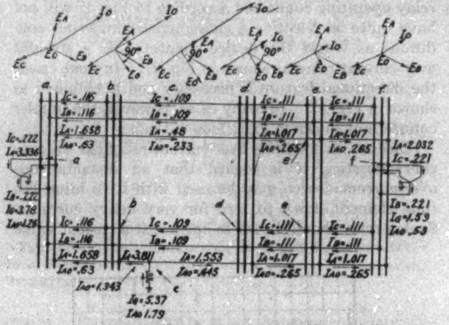
EA
Io
Eo
EB
EC
90°
a
b
c
d
e
f
Ic=.116
IB=.116
IA=1.658
IAo=.63
Ic=.109
IB=.109
IA=.48
IAo=.233
Ic=.111
IB=.111
IA=1.017
IAo=.265
IA=2.032
Ic=.221
IB=.221
IA=4.59
IAo.53
Ic=.222
IA=3.336
IB=.222
IA=3.78
IAo=1.26
IA=3.811
IA=1.553
IAo=.645
IAo=1.343
IA=5.37
IAo 1.79

FIG. 14—CURRENT DISTRIBUTION AND VECTOR RELATIONS EXISTING WITHIN RELAYS

For system as shown in Fig. 11 and with a 10 per cent fault resistance

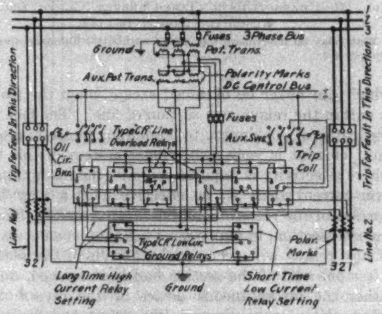
1
2
3
Fuses
3 Phase Bus
Pot. Trans.
Ground
Aux. Pot Trans.
Polarity Marks
DC Control Bus
Fuses
Type "CR" Line Overload Relays
Aux. Sw.
Trip Coil
Oil Cir. Bkr.
Trip For Fault In This Direction
Type "CR" Low Cur. Ground Relays
Polar. Marks
Line No. 1
Line No. 2
3 2 1
Long Time High Current Relay Setting
Ground
Short Time Low Current Relay Setting

FIG. 15—LINE AND GROUND PROTECTION FOR BOTH PARALLEL- AND SINGLE-LINE OPERATION USING DIRECTIONAL OVER-CURRENT RELAYS

The diagram shown in Fig. 15 is more desirable for the conditions shown in Fig. 12C. This diagram is similar to that shown in Fig. 4A, except that the ground relays are included.

In order to avoid using high-voltage potential transformers, the connections shown in Fig. 16 may be employed. As illustrated by Figs. 10 and 12B, the current flowing through the fault is largely supplied through the neutral of the transformer bank nearest the fault. Thus, instead of using a potential as shown in Fig. 13, the neutral current from the power banks may be used to determine the relative direction of current flow in a line. The currents in the line and in the neutral of the transformer bank are approximately in phase, so that the relay should be so designed as to have the maximum torque when the currents in the residual circuit of the current transformers and in the neutral connection of the power banks are in phase. The connections shown in either Fig. 13 or Fig. 16 are

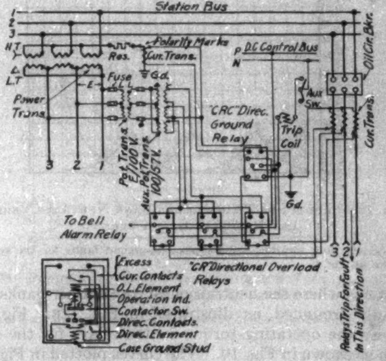
Station Bus
1
2
3
H.T.
L.T.
Polarity Marks
Res.
Cur. Trans.
Gd.
Fuse
E
Power Trans.
P
N
D.C. Control Bus
Oil Cir. Bkr.
Aux. Sw.
"CRC" Direc. Ground Relay
Trip Coil
Cur. Trans.
Pot. Trans. E/100 V.
Aux. Pot. Trans. 100/57 V.
3 2 1
Gd.
To Bell Alarm Relay
Excess Cur. Contacts
O.L. Element
Operation Ind.
Contactor Sw.
Direc. Contacts
Direc. Element
Case Ground Stud
"CR" Directional Overload Relays
Relays Trip For Fault In This Direction

FIG. 16—DIRECTIONAL OVER-LOAD AND DIRECTIONAL GROUND PROTECTION

Using definite time, residual, over-current relays and low-tension potential transformers

Rear view "CRC" directional ground relay is shown in lower left-hand corner

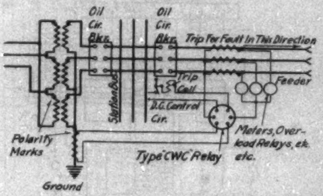
Oil Cir. Bkr.
Oil Cir. Bkr.
Trip For Fault In This Direction
Feeder
Trip Coil
Station Bus
D.C. Control Cir.
Polarity Marks
Meters, Overload Relays, etc.
Type "CWC" Relay
Ground

FIG. 17—TYPICAL DIAGRAM OF CONNECTIONS FOR GROUND PROTECTION USING THE INVERSE TIME, RESIDUAL, OVER-CURRENT, GROUND RELAY

equally good in determining the location of the fault.

*Inverse-Time Ground Relays.* The diagram shown in Fig. 17 is an alternative for, and under certain conditions, an improvement over that shown in Fig. 16. This scheme was first devised and put into service by Mr. Roy Wilkins.[3] The residual relays used here are inherently directional and in addition, operate with an inverse characteristic that is quite suitable for systems where the neutrals of all transformer banks are solidly grounded, as illustrated in Fig. 12B. Fig. 18 shows the operating torque on the relays for the system as shown in Fig. 10. The curves plotted in Fig. 18 are the products of the current in the transformer bank times the current in the line at any point on the system. This is the product which would tend to operate the residual current relay when connected as shown in Fig. 17. The operating tendency of the relay decreases rapidly as the fault approaches the adjacent substation bus, so that the quickest acting relay is that which is closest to the fault. In this respect, the relay has the characteristic of the impedance relay. After the breaker closest to the fault has cleared, the current through the relay on the far end of the faulty section increases and causes increased operating torque.

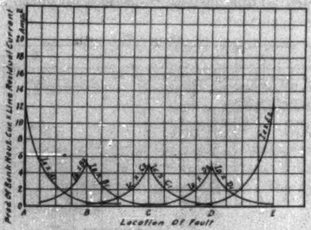

FIG. 18—PRODUCT OF TRANSFORMER BANK NEUTRAL CURRENTS AND RESIDUAL LINE CURRENTS

For any fault location and for phase-to-ground faults for the system shown on Fig. 9

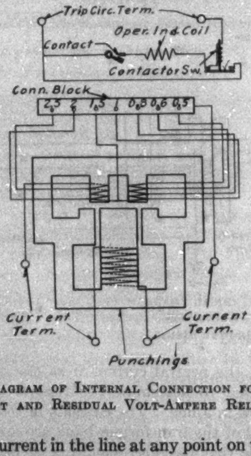

FIG. 19—DIAGRAM OF INTERNAL CONNECTION FOR RESIDUAL CURRENT AND RESIDUAL VOLT-AMPERE RELAYS

By actual calculations, it may be shown that the relay operating connected according to Fig. 17 will not have quite so selective a characteristic under all conditions as would the device connected as a straight over-current relay as shown in Fig. 21. In some cases, the directional feature is necessary and is obtained as shown in Fig. 17. In many cases, however, the simpler connections shown in Fig. 21 should suffice.

Since an inverse time over-current relay has suitable characteristics, it is logical that an instantaneous over-current device may be used with it to bring the time element down to zero for very heavy currents. Such a relay should be set to operate at a current value which can never be obtained except when the trouble is within the relays own section of line. The fact that the ratio of maximum to minimum phase-to-ground fault current is very small, for a system of this type where selectivity is required, permits the instantaneous over-current relay to be effective over a very large portion of the transmission line. Thus, with a fault in the mid-section, in many cases instantaneous operation of the relays will occur at both ends of the section. After one end of the section had been opened, due to either the instantaneous device or the inverse time relay, the current through the other end increases, increasing the likelihood of the operation of the instantaneous device at the far end.

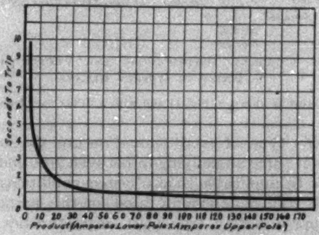

FIG. 20—CHARACTERISTIC TIME-CURRENT CURVE FOR THE RESIDUAL-CURRENT RELAYS

With relay on 0.5-ampere tap, No. 5 setting, the minimum operating product is 2

The diagram of internal connections of an inverse-time-directional current relay is shown in Fig. 19. Working on the watthour meter principle, it is quite evident from this diagram that the relay connected as shown in Fig. 17 would be directional. The characteristic curve for this relay is shown in Fig. 20.

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[3] *Electrical World*, November 22, 1924, p. 1101.

As previously mentioned, the inverse time relay may be used as a simple residual over-current device. Thus, at a switching station similar to that shown in Fig. 21, where neither a low-voltage nor a high-voltage potential transformer source is available, the ground relay may be applied and used as an inverse time over-current device. The relay may be so set that proper selectivity may be obtained at this point so long as three breakers are closed. If only two breakers are closed, in case of any fault, the tie will be dropped and it makes no difference which relays operate.

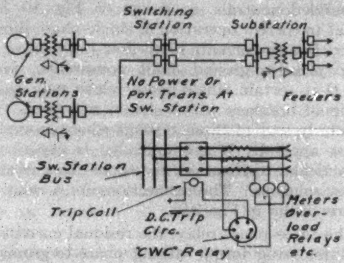

Switching Station
Substation
Gen. Stations
No Power Or Pot. Trans. At Sw. Station
Feeders
Sw. Station Bus
Trip Coil
D.C. Trip Circ.
Meters Over-load Relays etc.
"CWC" Relay

Fig. 21—Application of the Residual-Current Relay to a Switching Station Without a Source of Secondary Potential

A modification of the connections shown in Fig. 17 is that shown in Fig. 22. Here, a volt-ampere relay is used, the internal connections of which are similar to those shown in Fig. 19. The relay depends upon the principle that the product of the residual current and the residual voltage is greatest when the fault is close to the relay, with the result that the relay closest to the fault operates fastest. In addition to this, the relay is directional.

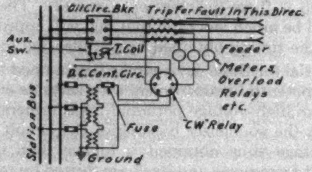

Oil Circ. Bkr.
Trip For Fault In This Direc.
Aux. Sw.
T. Coil
Feeder
D.C. Cont. Circ.
Meters, Overload Relays etc.
Station Bus
Fuse
"CW" Relay
Ground

Fig. 22—Typical Diagram of Connections for the Residual Volt-Ampere Relay

On a system as shown in Fig. 12c, the residual voltage, or three times the zero phase sequence voltage, increases from each end of the transmission line to the fault. The vector diagrams given in Fig. 14 illustrate the largest product closest to the fault.

The operating forces on this relay would be as shown in Fig. 23 and would apply to the system shown in Fig. 9. Quite clearly, the relay closest to the fault would operate much faster than any other relay on the system. This is true if the relay is so designed that the torque is proportional to the product of zero phase sequence currents and potentials as mentioned above in the discussion of the phase relations in the directional relay in connection with Fig. 14.

This volt-ampere product may be obtained quite accurately by an approximation. The unbalanced voltage, or zero phase sequence voltage which is used on the relay, is usually due to the drop through transformer banks plus transmission lines up to the relay. The phase angle between this voltage and the residual current may be as much as 80 deg. Taking this as the maximum, one may set the relay so as to secure the maximum torque when the phase displacement is 55 deg. The conditions of the system may then change so that

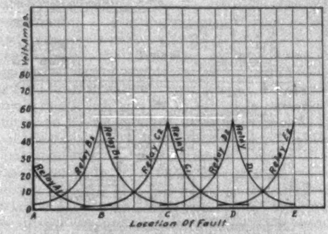


Fig. 23—Product of Zero Phase Sequence Voltages and Zero Phase Sequence Currents

For various phase-to-ground fault locations on system shown on Fig. 9

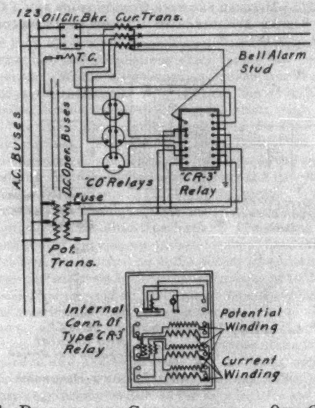

1 2 3
Oil Cir. Bkr.
Cur. Trans.
T. C.
Bell Alarm Stud
A.C. Buses
D.C. Oper. Buses
"CO" Relays
"CR-3" Relay
Fuse
Pot. Trans.
Internal Conn. Of Type "CR-3" Relay
Potential Winding
Current Winding

Fig. 24—Diagram of Connections for Over-Current Protection Using a Three-Phase Directional Relay

the phase displacement varies from 80 deg. (0.174 power factor) to 30 deg. (0.867 power factor) without introducing a volt-ampere error of more than 10 per cent. Due to the inverse characteristic of the relay, this small error should cause not more than 5 per cent error in relay time; and this is permissible since approximately the same error is applied to all relays. Therefore 55 deg. is standard, but this should be modified for special cases such as are met when high resistance is inserted on all neutral connections.

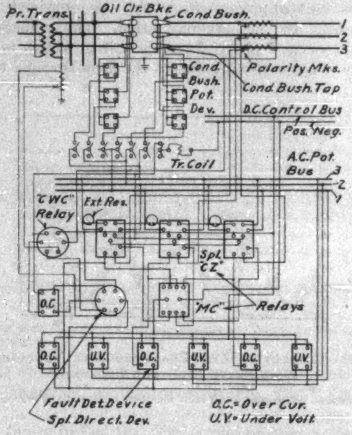


Fig. 25a—Diagram Showing Connections for a Complete Relay Scheme Applicable to a Complex Interconnecting System

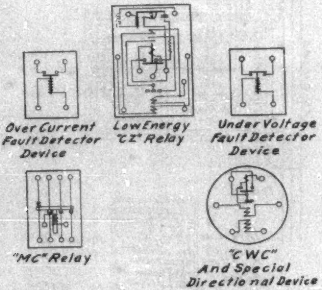

Over Current Fault Detector Device
Low Energy "CZ" Relay
Under Voltage Fault Detector Device
"MC" Relay
"CWC" And Special Directional Device

Fig. 25b—Internal Wiring Diagrams

The application of this relay need not be restricted to systems where the neutrals of all power banks are solidly grounded. Since the zero phase sequence voltage on practically any system will be largest on those relays closest to the fault, it can be used in preference to the definite time relays and gain some improvement of timing over them. The objection to this application lies in the difficulty in making the correct setting.

*The Use of the Polyphase Directional Relay.* The distribution of current on systems with a multiplicity of grounded neutrals, as shown on Fig. 10, is often inimical to correct operation of single-phase directional relays. Heavy currents often flow in all three phases during phase-to-ground fault conditions, with the result that certain single-phase relays may cause the clearing of breakers which should not open. This is particularly true of those systems where ground relays are not applied. Where difficulty is experienced in this particular application, the three-phase relay offers the best solution The connections for a relay of this type are shown in Fig. 24.

In the three-phase relay, the residual current causes a predominating torque during phase-to-ground fault conditions so that the currents in the good phases cannot cause faulty operation. Similarly the fault currents on such a system are always sufficiently large so that the load current will never affect the relay in such a direction as to prevent proper operation.

## A Typical Relay Installation

Fig. 25 represents a composite picture of relays suitable for application to a system as shown in Fig. 9. Impedance relays are used for protection against phase-to-phase faults, so that the maximum time of relay operation is three-quarters of a second. The average time will be much less than that and will approach very closely the timing obtained by parallel-line protection.

Potential for these devices may be obtained from low-voltage potential transformers with suitable compensators, from high-voltage potential transformers, or from a tap on the condenser bushing of the circuit breaker. The voltage thus obtained is higher than desirable, and must be reduced and its phase shifted by means of a small stepdown transformer and network, according to a method developed by J. F. Peters.

The load conditions on the system here shown are assumed to be such that fault currents of less than full-load magnitude must be guarded against. For this reason, low-current setting impedance relays are used and these relays are normally short-circuited by the auxiliary relay contacts. The fault detector relays operate under conditions of either over-current or under-voltage to remove this short circuit from the impedance relay coils. The residual relay is used to obtain the selective timing necessary for protection against phase-to-ground fault. In addition to the inverse time residual relay, an instantaneous over-current relay has been added to increase the speed of operation over that afforded by the residual relay for certain fault conditions. For this particular application, a directional instantaneous over-current relay was necessary and the directional element has therefore been included in a separate case.

This protective scheme compares very favorably with the ideal system for interconnections as previously specified. It has the following advantages:

1. The quick clearing of faults.
2. System operating set-up does not affect relay operation.
3. Relay system permits unlimited system extensions and revisions without necessitating increased relay timing.
4. The relay system should necessitate little or no change on the installed relay equipment protecting the individual systems combined by the interconnection.
5. Relays afford protection against bus faults.
6. Back-up protection against faulty operation of relays or breakers is afforded by this system of protection.
7. High-voltage potential transformers are not required. The breaker equipped with bushing type current transformers supplies both current and potential for the relays. Potential may also be obtained from low-voltage potential transformers.
8. The relay equipment is simple, standard, and economical.

## Discussion

**H. D. Bradley:** It might be well to point out in connection with the potential and ground relay, as mentioned, that there is a possibility of improper operation unless the potential transformers are single-phase. I refer to the scheme in which the star-delta-connected potential transfers were used, with the neutral of the star side grounded.

We had some experience along that line on lower voltage systems using three-phase potential transformers and learned that when a ground occurred on the system the fuses were blown and the relays were rendered inoperative, or operated incorrectly. The ground phase of the transmission line put a short circuit on one phase of the potential transformer, and due to the coupling of the magnetic circuits it virtually placed a short circuit on the potential transformer and resulted in blowing the fuses on the other phase. It is also possible in some cases to get the improper operation on the potential in directional relays.

We are getting away from that sort of operation by putting on a lock-out device similar to that described in the author's paper.

In the New York system we have a source of back feed to the 132-kv. cable which permits us to use a directional ground relay. This, we think, can be set to operate to pick up on less than 100 amperes.

**E. E. George:** (by letter) Perhaps the only statement that might be questioned by some is that referring to the hazard of high-voltage potential transformers. High-tension bushings are used on switches and power transformers with so little trouble that the question of their hazard probably does not prevent their wider use.

The balanced pilot-wire scheme in Fig. 1 looks very good for short lines.

It is to be hoped that we will soon get abundant operating experience from the industry on the use of carrier-current pilot protection, especially on intercompany tie lines.

There is a demand for a relay which will open tie lines when an out-of-step condition prevails.

The scheme (shown in Fig. 21) of using a directional ground relay as a straight ground relay to get the same timing characteristics is very ingenious and should be applicable in many locations.

It is possible to use the scheme shown in Fig. 17 with a very small grounding transformer. In fact we have one installation where the grounding transformer cost less than three potential transformers would have. Since the phase angle is so small between the ground current in the grounding bank and the ground current in a faulty line, there is little opportunity for this relay to work incorrectly on account of variations in power factor. Such variations are a liability of the type of ground relay shown in Fig. 16.

It is very encouraging to see the discussion of the advantages of ground relays. Operating experience seems to bear out all of the advantages claimed.

In enumerating the advantages of ground-relay protection, perhaps some mention should be made of the necessity of providing good bushing current transformers and of the advisability of testing them with current in one phase only after all connections have been completed, so as to get the full by-passing effect of the two phases which are not energized, as well as of the high impedance in the neutral circuit which does not apply for phase-to-phase faults. These difficulties are being overcome by the use of better iron in bushing current transformers, the use of larger current transformers containing more iron, and by the use of two current transformers in series per phase, which is standard practise with several companies. Ground tests at full system voltage provide the best over-all check of relay type, setting, and connection.

The diagram shown in Fig. 2 is very interesting, but a little more explanation might be desirable. For instance, it should be made clear whether this type of relay has the same time characteristics with the currents in the two coils 180 deg. out of phase as when they are in phase.

There is an application of selective differential relays for auto-transformers on interconnections which has not been touched on in this paper. Where interchange substations consist only of a grounded auto-transformer with only one line at each voltage, it is possible to use a selective differential ground relay, balanced by use of auxiliary auto current transformers for a through flow of ground current. The additional ground current supplied by the auto-transformer will prejudice the balanced relay toward the line in trouble, leaving the auto-transformer and its tertiary load connected to the good line. In making the balance it is necessary to assume that the through current varies inversely as the transformation ratio of the auto-transformer. This scheme has been in successful operation on our system for about two years.

One feature, not touched on in the present paper, which acts to discourage the wider use of potential-operated relays of the power directional type or residual volt-ampere type is the lack of any universal relation between power factor and fault conditions on the system, especially on interconnected systems. Phase angle between load current and phase voltage varies over a wide range under normal and abnormal operating conditions, without any faults on the system. Even under fault conditions the phase angle may vary nearly 90 deg. at the same location and is widely different at various locations even on the same system. The same statements apply to residual potential and ground current.

The above conditions explain the operating results given below which have been obtained by certain companies in this territory.

1. Power directional relays are of little value on interconnected systems.
2. Impedance relays are reasonably satisfactory.
3. Directional ground relays of the type using two current elements and connected up as per Fig. 17 in the paper under discussion have been remarkably satisfactory.

4. Selective differential relays have been very satisfactory when properly set and interlocked.

5. Directional volt-ampere relays have given some trouble due to variation in power-factor relations.

The foregoing comments are naturally based on operating experience under conditions that may or may not be general in the industry.

**L. F. Kennedy:** The crux of this whole situation is to maintain the stability of the system which in turn requires very rapid clearing of faults. This is also tied up with the accuracy that may be obtained, because without accuracy we cannot get down to minimum time settings.

Further, the bus sections must be treated as part of the line and whatever protection is provided necessarily covers these.

One point which has not been discussed is the protection of the power transformers used in the interconnections. These transformers today are, in many cases, of the three-winding type and the protection provided here is further complicated by the use of tap-changing arrangements.

The so-called impedance relay in its principle and theory appears very well adapted to single-line operation. However, we feel that there is still a great deal of development to be done before this relay is ready for final use by the operating companies. At the present time it appears that the adjustment and maintenance is more complicated than can be stood for a very extended length of time. Therefore, it appears that the manufacturers must continue their investigations, and I feel certain this is being carried on by the leading companies.

The use of ground relays, either of the quantitative or directional type, the directional type being polarized either by voltage or current as the conditions permit, have met with a very high degree of success, and operating conditions seem to indicate that more and more importance should be given to the protection against ground faults since with the higher-voltage systems we run into more ground faults than on any other type. Nearly every case of short circuit at the present day eventually goes to ground, and therefore in the final analysis the ground relay is the thing of greatest importance.

The situation, as it stands today, indicates that for parallel-line operation balanced hook-ups with the back-up protection necessary provided by over-current relays may be more desirable than anything else because of the simplicity and the fact that they are well known and it does not seem justifiable to ask the operating companies to spend too much time and money with schemes which are not in the final state of development.

In conclusion, let me emphasize once more that the main problem confronting both the operating companies and the manufacturers is to find some way of shortening the time necessary to clear a fault. If, as Mr. Jamieson has pointed out, we could catch the incipient fault it would be ideal. However, catching the incipient is still a problem of proper selectivity.

**L. R. Janes:** There are three questions that I should like to ask Mr. Graves concerning ground relays.

First: Are ground relays applicable for clearing "partial short circuits" on overhead systems such as we have in this territory? By a "partial short circuit" I mean a condition similar to that resulting from the breakdown of an insulator thus leaving only the pole or crossarm for insulation. The case of a conductor falling to dry earth is another example.

Second: As I understand it, the ground relay is only applicable for clearing phase-to-ground faults. Is phase-to-ground fault protection satisfactory and sufficient for overhead lines? In other words are practically all faults from phase to ground or does experience show that a considerable percentage are from phase to phase?

Third: Consider the case of a generating station supplying several substations located at points scattered along a transmission-line loop. If ground relays only are installed at the generating station on each of the two out-going lines and a fault occurs approximately half-way around the loop which is the point most remote from the generating station, will not the fault currents in each branch of the loop be approximately equal and thus cause both lines to open instead of only the one containing the fault?

**F. D. Wyatt:** On power systems using neutral resistance for fault-current limitation, the relay current during ground faults necessarily is of small value. The ground relay becomes of increasing importance on the power system using the neutral resistance for current limitation, and that its operation should be dependable is one of the difficulties to be reckoned with. The ground-relay scheme must involve a sensitive relay whose sensitivity and reliability depend largely on the range of fault currents for which it must operate.

The paper shows one of the factors controlling the range of variation, namely, variation in generating capacity and point of generation, which may cause wide variation in the magnitude of fault currents. The paper also brings out the complications which are necessary in the relay circuit to compensate for the wide range of fault currents. For ground relaying, the situation is further complicated by the wide variation possible in the resistance of the fault and also a variation in the number of grounded neutral points.

The ground relay should also differentiate between low-value fault currents and small residual currents which may result due to the character of the relay circuit and system connections. Ordinarily, the balanced protection applied to a pair of lines, it is assumed that the lines are of equivalent and equal impedance characteristics. This, however, is not always the case so that when lines are of unequal length it is necessary to make proportional adjustment for the distribution of current. The problem is a little more difficult if the lines are not of the same power-factor characteristic.

Another factor which enters into the setting of balanced line relays is the possibility of induced voltages being applied to a good pair of lines by external circuits adjacent to the balanced pair. That is, assume that there is a line which is a part of a good pair running adjacent to another circuit which is in trouble with a phase to ground fault. Due to the current in the faulty circuit, potentials will be induced on the balanced pair which will cause a circulating current to flow in the loop formed by the balanced pair. Then a current will flow through the ground relays and if they are set at too low a current value an incorrect relay operation on the pair of good lines will occur.

If I may, I should like to answer the last question of Mr. Janes. That situation can be taken care of by using directional ground relays instead of current ground only. At the power station or substation where neutral resistors are available, or neutral current can be measured, directional features can be secured where there is not a transformer bank or transformer neutral. This may be secured by using potential transformers arranged to give an inside delta potential which is the residual voltage at the substation.

**B. M. Jones:** (by letter) The scheme shown in Fig. 15 is admirably suited to our system, for it simplifies the present scheme of balanced parallel-line protection which we have been using, in that it removes several complications. On our system we are not confronted with small fault currents wherein these fault currents are less than the load currents, for our system is relatively compact and a considerable amount of ground current flows in all ground faults as well as short circuits.

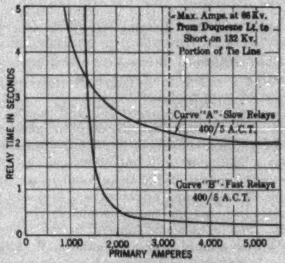
Fig. 13 shows a diagram for directional line and ground protection for a single-circuit 3-phase transmission line. This particular scheme is standard with our company, and I believe that we were one of the first companies to adopt such a scheme. We have this scheme in use very widely on our 22-kv. system and to a limited extent on our 66-kv. transmission line. This scheme of directional ground protection was described by Mr. Dodds and myself in a paper presented before the Institute in Detroit in June of this year.

Fig. 25A shows a complete relay scheme applicable to a complex interconnecting system which uses thirteen relays for tying together two lines. This is a vast number of relays and a correspondingly complicated connection; and to my mind strenuous efforts should be made to simplify such a scheme. While such a scheme may look well on paper and may suit the engineers in the office, the relay trouble shooters are certainly going to have their troubles in maintaining such a mass of connections as this scheme shows.

While our company has used single-phase directional relays in all cases in the past, I can easily see that there are certain applications wherein the polyphase directional relay has some advantage over the single-phase relay. We have a certain case in mind on our own system now, where we are looking into the advantages to be gained through the use of polyphase relays.

It has been our experience, and I feel that other operating companies have encountered the same situation, that complicated relay schemes are hard to maintain and require a very high grade of skilled help, and eventually cause considerable trouble and inconvenience, and sometimes considerable embarrassment to those responsible for the relaying of the system.

Our company leans very strongly toward making all relay schemes as simple as possible to provide adequate protection and at the same time have as few a number of schemes as might be necessary.



The Duquesne Light Company has a 36,000-kv-a., 66/132-kv. tie line with the West Penn Power Company, our immediate neighbor, which line is 2½ mi. long. There is a transformer bank in our Colfax Power Station, which steps our bus voltage to 132 kv. for this line.

The particular relay scheme used for this is very simple and effective. The idea behind this tie was to hold the tie in unless there was trouble on the tie itself, or when serious trouble on either system hung on for an unreasonably long time. On this basis, the maximum benefit would be obtained from the use of the tie line.

The accompanying sketch shows the time-current characteristics of the relay scheme used, which is briefly the installation of two sets of over-current relays at each end of the tie line which are set alike in pairs.

One set of relays at each end of the tie line are "fast relays" and the other set "slow relays." The "fast relays" operate for trouble on the tie line itself on one side of the bank and will cause enough current to flow in the closest relays (closest electrically, from an impedance point of view), to operate, thereby breaking the tie at one end. The "slow relays" will operate for trouble beyond the bank on either side, and are set slow enough to allow the relays of the power company in trouble to clear the trouble. In case the power company in trouble does not clear itself of trouble within the time setting of the slow relays, they will break the tie, thereby relieving the good system from the difficulties of the system in trouble. The ground relays are set same as the fast relays, and of course operate for trouble on the tie line itself.

Our experience has shown that this relay scheme operates as it was planned to operate, and occasions have arisen whereby the slow relays have taken out the tie when the system in trouble did not cut the trouble clear promptly.

**H. H. Green:** (communicated after adjournment) The carrier-current protective scheme referred to brings into the protective-relay field principles which are new to this phase of power-system engineering. The pilot-wire scheme, which is the basic relay principle involved, is not new and is ideal for transmission-line protection. This relatively new carrier-current scheme has real possibilities and will require only an adequate operating record under service conditions before taking its proper place as a super-power system protective scheme.

The scheme outlined in detail, requiring the use of special and standard relays, is based on relay principles in common use. The need of a quantitative study of short-circuit currents, in order to apply and obtain the maximum benefits with the relays now available, is quite obvious. The development of the Method of Symmetrical Components, for studying fault conditions, has placed in the hands of the protection engineer a means of handling this difficult phase-to-ground short-circuit problem, and the application of this method to the calculating table permits the handling of phase-to-ground short circuits on complicated systems, as 3-phase short circuits have been handled. The calculating table is, therefore, made still more indispensable as the type of construction of the super-power systems will result in phase-to-ground faults being in the majority. The calculating table is more indispensable than the slide rule, in its field, in relation to the protection of a large system and should, figuratively speaking, be at the protection engineer's elbow.

The need of a quantitative study of the problem makes it desirable to use recording equipment in the field to obtain accurate measurements of the quantities involved. A form of oscillograph, which is automatically put in service at the time of the fault, lends itself to this type of investigation and such records are of real assistance.

**H. C. Graves, Jr.:** Mr. Bradley has described two features which may cause incorrect relay operation. The first of these brings out the fact that 3-phase core-type potential transformers cannot be used in general for relay protection, particularly when directional ground relays are used. Such potential transformers must be either single-phase transformers or of the 3-phase shell type. The second point made by Mr. Bradley is that directional relays may operate incorrectly if the overcurrent contacts open so slowly as to permit the directional contacts to close and cause faulty tripping before the overcurrent contacts open. One correction for this trouble is also indicated.

In the majority of cases where such trouble occurs, it will be found that it can be corrected by increasing the contact spacing of the directional element. It should be noted that this directional element need not be instantaneous, but need only be fast enough always to close before the closing of the overcurrent contact. Overcurrent relays of the ungeared type will open their contacts in from 3 to 4 cycles (60-cycle basis) after the relay is de-energized. This quick opening of the contacts permits the relay to handle the majority of cases described by Mr. Bradley without causing faulty operation. In those few cases where the contact spacing cannot be increased sufficiently to avoid the trouble, directional overcurrent relays may be employed. These have directional contacts connected in series with the upper pole circuit of the overcurrent element, thus preventing operation of the overcurrent element until power flow is in the direction which causes closing of the directional contacts. The overcurrent contacts are then permitted to trip the circuit breaker directly.

This arrangement is very simple but involves special design of the upper pole windings of the overcurrent element.

The diagram shown in Fig. 2, referred to by Mr. George, brings out the different operating characteristics of this relay depending upon whether the currents in the two coils are in phase or are 180 deg. out of phase. Curve *A* represents the in-phase condition, or the condition where currents flow out on both the good line and the bad line. Curve *B* illustrates the condition which would exist at the other end of the line, or the relay characteristics with the currents 180 deg. out of phase.

The point made by Mr. George relative to the necessity for having current transformers of good characteristics for operating residual relays is of importance. Residual relays have a relatively low volt-ampere burden, but the impedance is usually higher than the line protective relays because of the fact that lower current taps are used. As a result of this fact a phase-to-ground fault causes a voltage to be built up across the residual relays which tends to cause the fault current to circulate back through the bushing type current transformers in the good phases. Unless the characteristics of the bushing-type current transformers are good, this leakage current will be so appreciable as to affect the relay operation.

Mr. George also brings out the fact that the use of volt-ampere relays is hindered by the fact that the phase angle under fault conditions is quite variable. This in itself would indicate that the volt-ampere relays could be used to advantage on systems whose neutrals are grounded through a grounding resistor. This tends to establish a fairly constant angle between the residual voltage and residual currents. Thus advantage may be taken of the fact that the residual voltage and residual current invariably increase as the fault is approached.

Mr. Kennedy stated that "The so-called impedance relay in its principle and theory appears very well adapted to single-line operation." We are pleased to add that operating experience with relays of this type indicates that they also work out in practise. At the present time both types of relays can be used with the assurance that their operating characteristics are definite, and that they will therefore operate according to the adjustments made.

On complicated systems it is necessary to ascertain the distribution of and value of short-circuit currents in order to determine breaker ratings and relay settings. To make this study it is necessary first to determine the reactance or impedance values of the system, set up these values on a calculating board and read the short-circuit current for both maximum and minimum conditions of generating capacity. This involves a considerable amount of labor. Knowing the current values for the minimum condition of generating capacity, the relay setting of definite time relays may immediately be established. For inverse-time overcurrent relays this is not the case since the relays must be set so as to secure selectivity under the maximum condition of generating capacity as well as minimum condition.

After the short-circuit study has been made, it is as simple to determine the setting and operating time of the impedance relays as is the case with inverse-time overcurrent relays. The fact that the impedance relay is practically independent of conditions of generating capacity simplifies the determination of the time required for the operation of the relay.

The first question asked by Mr. Janes can best be answered by the statement that the present design of ground relays permits them to operate when the current flowing to ground is such as to cause 0.5 ampere to flow in the secondary of the current transformers. This is somewhere in the neighborhood of 12 per cent of full-load current. These relays are therefore much more sensitive than can be the relay protecting against phase-to-phase faults. If the fault is such as not to permit this value of current to flow, the additional load imposed on the transmission system is probably so small as to be negligible until the faults develop into a phase-to-phase fault. When this happens the phase protective relays will clear the fault. In answer to the second question, I should say that the general concensus of opinion today is that both phase-to-phase and phase-to-ground fault protection is necessary. If only one type of protection be used, it should be the phase-to-phase protection. The greatest majority of faults on a system consist of phase-to-ground faults, but on most systems phase-to-phase faults will occur which will not tend to operate the residual relays.

A general answer to the third question is difficult in view of the fact that almost every case must be handled individually. In general, for systems of this type, residual relays will not materially assist in reducing the relay time unless the system is similar to that shown in Fig. 10. On the average system where the loop is grounded at only one end, and particularly where the pole hardware is not grounded and no overhead ground wire is used, residual relays will be advantageous because of their increased sensitivity, but in general will not cause any quicker clearing of phase-to-ground faults than will the phase protective relays in cases of phase-to-phase faults. However, since the distance between stations is so short as not to permit the application of the impedance type of relay, it would seem possible to apply pilot-wire protection, at least to the shortest sections, and thus reduce the number of selective settings necessary.

Relative to the selectivity of operation of the residual relays, on systems as described by Mr. Jones, the treatment must be very similar to that used for protecting against phase-to-phase faults. For parallel lines the residual relays are usually cross-connected. The exception to this is the system described in Fig. 10 where the residual relay acts somewhat in the nature of an impedance type of relay so that the relay closest to the fault will always clear first thus assuring selectivity even in case of parallel lines.

Mr Wyatt has mentioned the problem which has been met by several operating companies wherein a faultly line induces a current in one of a pair of parallel lines, thus offsetting the balance in this supposedly balanced pair and causing operation of the relays. This usually occurs only for phase-to-ground faults, and one solution consists of increasing the settings of the balance relays. This solution is undesirable in view of the fact that it reduces the sensitivity of the ground relays, thus doing away with one of their major advantages. A second suggested solution consists in balancing the unbalance in the two pairs of parallel lines. The unbalanced current in the faulty pair of parallel lines will invariably be greater than that in the good pair. This difference in unbalances will cause a set of contacts to close which will permit the operation of the relays on that pair of parallel lines which has the greatest unbalance. The objection to this scheme lies in its complexity, and in the fact that the scheme cannot take care of unbalances at the neighboring stations. These relays must still be set high to avoid faulty operation. The relay solution here as in many other relay problems consists in designing the system so as to permit proper relaying without excessive cost.

Mr. Jones has found objections to the system of connection as shown in Fig. 25, because of its complexity. This we believe is just, and this system of connection should never be installed except in those extreme cases where necessary. However, as mentioned by Mr. Green, each part of the scheme consists of relay principles which have been in use for some time and have been proved, and thus an experienced maintenance crew guided by the short-circuit study and operating experience, should have no difficulty in determining the cause of faulty relay operation.

In conclusion, I should like to add that simplicity in the protection schemes invariably gives the best results. However, to be able to employ simple relay schemes, it is essential that the system layout be such as to permit these simple schemes to be used. Relay application is complicated because all systems are different. The system grows up and as it grows the relays are changed so as to take care of the newly developing conditions. The best results can be obtained only when the planning of the system and the scheme of protection go hand in hand.

# Alternator Characteristics Under Conditions Approaching Instability

BY JOHN F. H. DOUGLAS[1] and EDWARD W. KANE[1]
Associate, A. I. E. E. Associate, A. I. E. E.

***Synopsis.**—In this paper the comparatively recent discovery of generator instability is discussed. A method of testing synchronous machinery in the unstable as well as in the stable range is described. The results of tests performed on two machines is shown and discussed. The conclusion is drawn that the design of customary machines will have to be improved, synchronous condensers installed on many long lines, or inefficient underloading of units will have to be tolerated.*

## INTRODUCTION

Until recent years the loads on power systems were with a predominately lagging current. While the regulation of the generators was sometimes quite poor, nevertheless the operation showed high stability and the field rheostats were adequate to control the voltage without loss of synchronism. Perhaps because of this fact, and perhaps for other reasons, textbooks have shown practically no diagrams or full-load saturation curves for leading power factors. The student might well obtain the impression that the solution of the problem of regulation for such power factors would be carried out without difficulty, but when one attempts to carry out the solution, one meets with several obstructions of a theoretical nature.

Of late years the voltage and length of transmission lines have been increasing and the number of interconnections growing. Consequently the leading current load is becoming quite an item. At the same time due to attempts to improve customer power factor the lagging current load has shown a tendency to decrease. As a consequence, some curious phenomena have been noticed and reported: 1. A very unstable voltage on light loads when the line charging current is carried by too few units. 2. Inadequate field rheostat resistance to keep the voltage down. 3. The combination of lines and generator becoming self-exciting, that is, a resonance between the inductance of the machine and the capacity of the line, giving high voltage with the field circuit open. 4. Generators remaining in step with small reverse field excitations. 5. Generators slipping a pole when the reversed field excitation is increased, and before the voltage is brought down to normal. When this pole slipping takes place, there is a surge which causes the voltage to rise to considerably above normal.

The difficulties met in attempting to apply the A. I. E. E. rule for leading current loads is well illustrated in Fig. 1. The curve $O X$ is the no-load saturation curve; $F Y$ is the full-load zero power-factor lagging saturation curve, and $F Z$, the full-load unity power-factor saturation curve. The zero leading power-factor full-load saturation curve is shown by the line $A B C D$, or the line $A B C E$. The segment $A B$ is as much above the no-load saturation curve as the line $F Y$ is below it, as required by the A. I. E. E. rule. For saturations below this point, one is in doubt as to just how to proceed,but if it be assumed that the synchronous impedance is a constant, the segment $B C$ would be drawn parallel to the line $O X$. For voltages below $O C$ we meet another difficulty. If we continue the line toward the point $D$, we have a characteristic which, unlike the lagging characteristics, does not pass through the point $F$. If we reverse the segment $C D$, we are unable to account for the operation with reversed field currents and we must imagine a sudden 180-deg. shift of phase at the point $C$.

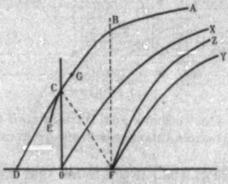


FIG. 1—ILLUSTRATING DIFFICULTIES IN ESTIMATING ZERO POWER FACTOR LEADING SATURATION CURVES

With the peculiar behavior of synchronous machinery reported and the obvious defects in the more usual theory before us, we determined to make some tests with leading current conditions and if possible, try to extend them into the region of unstable operation.

## PRELIMINARY TESTS

Our first tests were of a qualitative character. We sought to verify for ourselves just what took place when a generator lost control of its load. We connected an a-c. generator to a synchronous motor load, but did not take power from the motor. We overexcited the motor, loading the generator with leading current of low power factor. We included a field ammeter, armature ammeter, and voltmeter in the generator circuits. We attached a G. E. slip meter to the syn-

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[1] Both of Marquette University, Milwaukee, Wisconsin.

*Presented at the Regional Meeting of District No. 5 of the A. I. E. E., Chicago Ill., Nov. 28-30, 1927.*

chronous motor shaft, which we excited from the same 60-cycle supply that furnished power to the synchronous motor which drove the generator being tested. The amount of leading current was held roughly constant and varied the generator field current and generator voltage. The characteristic *A B C E* in Fig. 1 was obtained. At the point *E* there was a surge of voltage and current, the generator forged ahead one pole or the motor slipped a pole as indicated by the slip-meter differential turning 90 electrical deg. The voltage after the surge corresponded to the point *G*.

This experiment was considered to prove, in a general way, the results previously reported, and to indicate that further tests were worth while.

## TESTS OF GENERATOR CHARACTERISTICS BY A PUMP BACK METHOD

First of all it was determined to employ an opposition method of testing, in order to obtain, if possible, characteristics of the unstable condition of operation. This procedure was successfully used by one of the authors in testing synchronous motors in their unstable range, and reported on in the A. I. E. E. TRANSACTIONS, 1925; p. 164. It was found that the connections in Fig. 2 were suitable. The generator (1) was directly connected to an identical machine (2) with a movable stator controlled by the hand wheel (3). These machines were 15-kv-a. 1200 rev. per min. machines rated at 220 volts with a Y-connection. Machine (2) absorbed the power generated by (1). The losses were sometimes supplied by a d-c. motor belted to the set, and sometimes, from the connection shown to the 60-cycle line. The amount and phase of the current output of the generator could be controlled by the hand wheel (3) and rheostats (4) and (5).

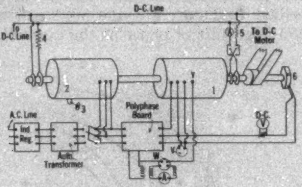


FIG. 2—CONNECTIONS FOR DETERMINING COMPLETE EXCITATION CHARACTERISTICS OF ALTERNATOR

The output of the generator was measured by a polyphase wattmeter; sometimes by the three-wattmeter method, using the neutral point on one machine. The line current and voltage were measured with the aid of a polyphase board. The phase angle of the terminal voltage with respect to the pole axis was measured with the contactor (6). This contactor was the usual point-by-point wave form apparatus, and was connected in series with one phase of the generator and a d-c. voltmeter, which was shunted by a condenser. The movable arm carrying the contacts could be turned about and their position noted on a degree scale. They were turned at all times so that the voltmeter gave a zero reading. The shift of the contacts from no load to the point under observation indicated the amount that the pole axis shifted with respect to the terminal voltage. This use of the contactor was developed by Messrs. Edwin Baldwin and Earle Lashway when seniors at Marquette University.

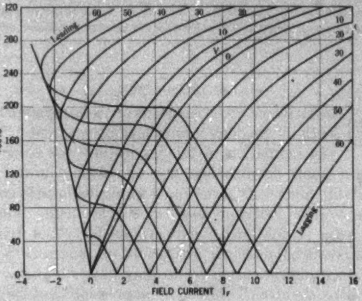


FIG. 3—EXCITATION CHARACTERISTICS OF ALTERNATOR ZERO POWER FACTOR LEADING AND LAGGING FOR CONSTANT ARMATURE CURRENT

In the first series of tests, the wattmeter was at all times kept at zero by the hand wheel. Currents were circulated by maintaining a difference in the excitation between the two machines. Runs were taken for armature currents of 60, 50, 40, 30, 20, and 10 amperes. Voltage, field current, and phase shift were recorded for each run. Owing to the fact that when the generator field was large, the motor field was small, and *vice versa*, the voltage seldom exceeded 270 volts. For the higher

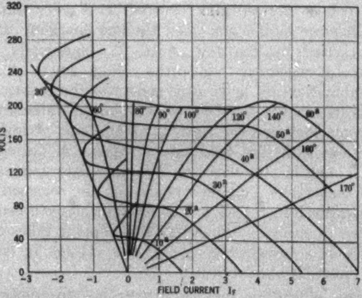


FIG. 4—ZERO POWER-FACTOR CHARACTERISTICS LEADING CURRENT IN REGION OF UNSTABLE OPERATION, FOR VARIOUS ARMATURE CURRENTS AND VARIOUS ANGLES OF POLE SLIP

voltages, therefore, the set was synchronized with the a-c. line. The data were in such form that it could be directly plotted in Figs. 3 and 4. Fig. 3 shows the voltage characteristics for zero power factor, Fig. 4 shows also the phase displacements in the unstable range.

It is to be observed that stable operating condition is shown with reversed current in the field, also that the lagging and the leading characteristics join at a common point *F*, and that the shift of 180 deg. is only gradually accomplished in the unstable range. A phase shift from 30 deg. to about 160 deg. occurs at a practically constant voltage. These "nose" shaped generator characteristics are believed to be novel.

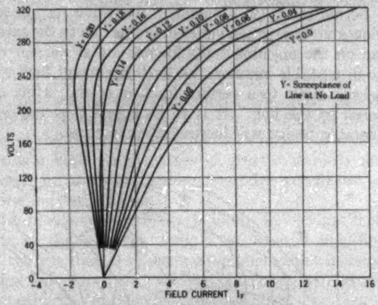


Fig. 5—Excitation Characteristics of Alternator at No-Load and Various Line Capacities

Since a transmission line connected to a generator at no-load represents a zero leading power-factor load of constant ratio of amperes to volts, it was thought to be of interest to take a series of cross curves from Fig. 3 representing constant equivalent single-phase "Susceptances" of values from 0.00 to 0.2 in steps of 0.02 amperes per volt. These cross curves are plotted in Fig. 5. It will be seen that with a charging susceptance of large value, the characteristics are quite steep and in some cases practically vertical. Under these conditions, voltage control is difficult. If it is not feasible to use synchronous condensers on such a line and under-excite them at light load, then it will be impossible to shut down too many units at light load. Of course if a considerable improvement in generator design is made, this conclusion may be modified.

The second series of tests was made at a current of 40 amperes, practically full-load rated current. For convenience, at voltages of less than 270 volts, each run was made with a constant phase displacement between the two machines. Above 270 volts, each run was made for a constant terminal voltage. In each run, the power factor was varied from zero lagging to zero leading by a proper variation of the two field rheostats. For each run the terminal voltage, power factor, and phase displacement of the rotor was plotted against the field current. Cross curves were taken from these for constant power factors and constant phase displacements of rotor. Curves for 0, 70, and 90 per cent lagging, and for 100, 90, 70, 50, 20, and 0 per cent leading power factors were taken. Curves for 10, 20, 30, 40, 50, 60, and 90 deg. phase displacement were taken. All these curves are plotted in Fig. 6.

It is to be observed that all the full-load saturation curves pass through one common point *F*; also that for power factors of less than 20 per cent leading current, it is possible to obtain stable operation with reversed field current. The line *E S F* passes through all the points where the curves are vertical and may be taken as the limit of stable operation. Below and to the left of this line, generator operation is unstable; that is, it will forge ahead a pole if it is free to do so. The phase displacements of the pole axis from the terminal voltage are small in the stable operating range and are considerably less at high saturations.

The hope for improved design and increased stability consists of being able to extend the nose of these curves toward the region of reversed field currents, and to lower the lower edge of this nose at the place where it intersects the Y-axis. Attention will be called in a later paragraph to the constant of the machine, which requires improvement.

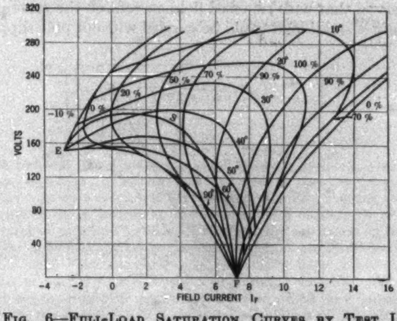


Fig. 6—Full-Load Saturation Curves by Test Loci of Constant Power Factor and Pole Slip Angle. Locus ESF of Stability Limit

## Tests of Generator Stability with Direct Loading

In the endeavor to determine the locus of stable operation, such as *E S F* in Fig. 6, by direct loading and actual observation of pole slipping, we took a 5-kv-a., 1800-rev. per min. 220-volts, three-phase Northwestern machine and connected it according to the diagram in Fig. 7. In this figure (1) is the alternator to be tested, driven through a belt by the d-c. shunt motor (2). The alternator delivered its power to synchronous motor (3), and this, in turn, to the alternator (4) and the a-c. line. By controlling the rheostat (5) in the field of the d-c. shunt motor the amount of power circulated could be controlled. The amount of leading current taken from the alternator could be controlled by the field rheostat (6) of the synchronous motor. The field of the alternator (1) was controlled by reversing switch (7) and rheostat (8). For convenience each run was taken at a constant field current of the alternator tested.

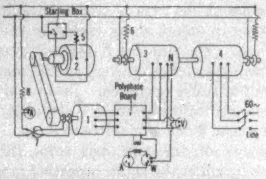


FIG. 7—CONNECTIONS FOR DETERMINING POINT OF POLE SLIPPING IN AN ALTERNATOR

For each point of data, the field rheostat of the d-c. motor was weakened until the generator slipped poles. This pole slipping was easily identified by the current and voltage surge which took place. Some practise was required, however, to secure readings at the point just before the pole slipping took place. It was observed that with reversed field current on the generator, only a small load could be carried without pole slipping taking place. Under these conditions, the generator slipped only one pole and regained synchronism. When the fields were excited in the normal manner, a considerably greater load could be carried without pole slipping; but when the critical load was exceeded, the generator fell out of step completely and continued to slip poles.

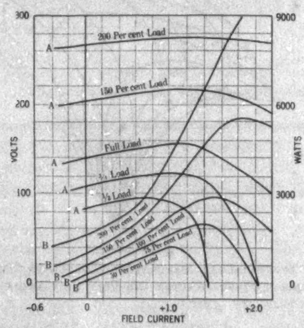


FIG. 8—STABILITY LIMITS OF VOLTAGE AND POWER IN AN ALTERNATOR FOR VARIOUS CURRENT LOADS

Readings of generator voltage and watts were taken for the slipping point and plotted against the armature currents, for six runs, during which the alternator field currents were respectively 2, 1.5, 1.0, 0.5, 0, and −0.5 amperes. Cross curves were taken from these for armature currents of 2, 1.5, 1, 0.75, and 0.50 times rated current. The cross curves thus obtained are shown in Fig. 8.

The curves shown agree in form fairly well with the curve *E S F* in Fig. 6. The voltage of the generator is too high at conditions of large leading current. The chief conclusions to be drawn from these curves are as follows: (1) The criterion of stability assumed,—namely, a vertical volt field-current characteristic,—is borne out. (2) Generator operation is unstable below a voltage which varies in proportion to the current load on the machine. (3) To operate at normal voltage in a stable manner, the leading current load must be kept down to a certain fraction of the rating connected to the line. It is to be hoped that improved generator design will increase that fraction.

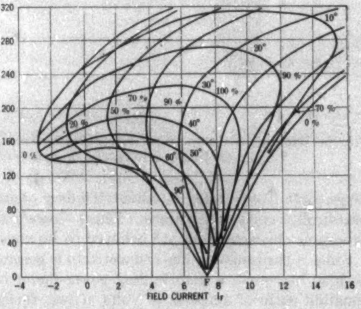


FIG. 9—FULL LOAD SATURATION CURVES COMPUTED BY BLONDEL. TWO REACTION DIAGRAM, LOCI OF CONSTANT POWER FACTOR AND POLE SLIP ANGLE.

## PREDETERMINATION OF GENERATOR CHARACTERISTICS WITH LEADING CURRENT

In the A. I. E. E. JOURNAL for February 1927, (p. 109), one of the authors proposed a method for computing the performance of synchronous machines. It was thought that it would be interesting to compute a series of curves such as shown in Fig. 6 by the method there outlined. It was felt that in view of the unusual and novel shape of the curves in Fig. 6, an agreement would give a satisfactory confirmation of the theory. The constants of the machine tested in this paper for two-phase connection are reported in the article cited. For the three-phase connection the following were assumed:

Direct armature reaction 7 amperes field current equivalent to 40 amperes in the armature. Transverse armature reaction, 3.5 amperes in the field equivalent to 40 amperes in the armature. Direct reactance 1/3 ohm per phase of $Y$, transverse reactance zero, and resistance 1/6 ohm per phase of $Y$. Saturation curve is as shown in Fig. 3.

With the constants in the above paragraph, the characteristics shown in Fig. 9 were computed. These should be compared with Fig. 6. We consider the agreement is very good, and believe that further theoretical studies of synchronous machines should be based on some form of the Blondel two-reaction theory.

The extent of the "nose" of the curves and the lower intercept of the nose on the Y-axis seems to depend chiefly upon the constant of transverse reaction.

### CONCLUSIONS

In this report various remarks have been made to point out results of significance. The most general conclusion to be drawn is this: By a reduction of the value of the transverse reaction with improved design, there is a hope for machines of greater stability and consequent improved behavior under conditions of low leading power factor.

The problem of stability is likely to become more acute as the voltages, lengths of transmission line, and the number of system interconnections increase, so that it is hoped that the manufacturers will be able to improve the stability of their machines.

## Discussion

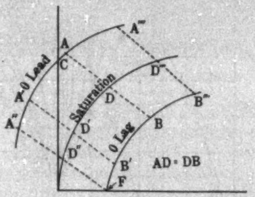
**B. A. Behrend:** This paper is timely and opens up a number of points which I wish to enumerate. First, it calls attention to the method of the A. I. E. E. for the determination of regulation and states that the method recommended for zero leading power factor is in error. As I have been instrumental in introducing the zero-power-factor method for the determination of the regulation of alternators,[1] I here state that the correct method, or at least the method which I recommended, consists in shifting the entire saturation curve along the line $A\ B$, either below the saturation curve for lagging currents, or above for leading currents.[2] This is the Potier-Behrend method which has been used by us continuously for twenty-eight years. Refinements of this method have been made from time to time but the fundamental simplicity and accuracy have been maintained. It is regrettable that the Standards Committee appears to have departed from this method as would be indicated by the statement made by the authors.

So far as I know the curves produced by the authors are novel. My second point deals with their attempt to join the leading-current zero-power-factor regulation curve to the point $F$ in their Fig. 1. In checking the curves of their Fig. 3, by the Potier-Behrend method I find a good degree of agreement with their curves. With a leading-power-factor load of a given amount the authors found that the generator would stand a small amount of negative excitation after which "the generator forged ahead one pole or the motor slipped a pole." Now, it would have been interesting if they had attempted to prevent this action so as to prevent the leading zero-power-factor curves becoming discontinuous. Negative rotor excitation can be compensated by leading stator excitation so long as the two fields remain in step. Theoretically within limits it makes no difference on which member the excitation is applied.

Twenty-five years ago we used to design alternators with good regulation so that it was not exceptional to have a generator with a short-circuit current six times the normal current and with a very "stiff" field. On such generators it is possible to run a negative excitation without the slipping of the rotor. Such curves have been run on fly-wheel type generators with great inertia and they have confirmed the Potier-Behrend method of regulation. Such tests should now be repeated on modern alternators with large armature reaction by resorting to special methods to keep the generator from falling out of step. There are several ways in which this can be done.

Thirdly, I should like to comment on the suggestion of the authors advising that improvements in alternator design should be made to secure greater stability on long lines of great capacitance. It is very essential that this be done but it would be regrettable if history had to repeat itself and if large generators would have to be built again with strong fields instead of strong armatures. The remedy might be worse than the disease.

The problem of stability is by no means a new one and much could be learned in the present predicaments from past experience. Perhaps one of the most difficult problems was the design of the generating plant for the United States Steel Corporation of its Indiana Steel Company's plant at Gary, Indiana, where fifteen 3000-kv-a., generators are operated in parallel by gas engines. In such cases it is necessary to take into account the stability of the generators so far as overload is concerned; and the stability in regard to oscillations which are dependent on the electric characteristics of the generators and on the total inertia of the unit. The generator and gas engine have a natural period of oscillation which can be calculated and this period must not coincide with any "forced" period which may happen to be in the system. I had charge of the design of this plant and it is gratifying to state that the calculated frequencies agreed so well with the actual frequencies that, in spite of light flywheels and virtually no damping in the pole pieces which were solid without copper dampers, the plant operated perfectly from the start. Now, the overload margin of modern generators is much curtailed on account of the weak fields and their natural period of oscillation is greatly increased for the same reason so that conditions of resonance are likely to disrupt the system. Blocking of governors has had to be resorted to in some of the largest plants to avoid such resonance. If a generator, slightly displaced from its position of equilibrium, performs an oscillation the period of which is nearly equal to the surge frequency of the line, no stable operation can be expected. Either a weaker or a stronger field, or a greater or smaller moment of inertia, would or might improve such a condition. It was my practise to test the generators for their natural frequency where the unit was used in connection with gas engines or steam engines and where



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[1] The Factors which Determine the Design of Monophase and Polyphase Generators," by B. A. Behrend, *Electrical World & Engineer*, Jan. 20, 27, Feb. 3, 1900.

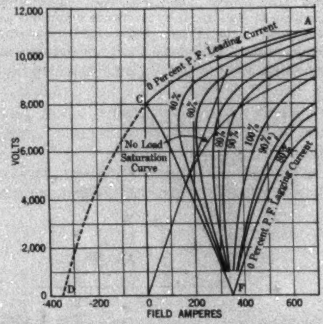
*The Experimental Basis for the Theory of the Regulation of Alternators*, by B. A. Behrend, TRANSACTIONS A. I. E. E., Vol. XXL, 1903, p. 497.

[2] "Sur la Réaction d'Induit des Alternateurs," by Alexandre Potier, *L'Eclairage Electrique*, July 28, 1900. This paper is based on B. A. Behrend's data and its Fig. 2 shows the regulation curves for zero lagging and leading currents.

there was a pronounced forced frequency going to be in the system. A similar course should be followed in connection with units which have to operate on long lines so as to predetermine as nearly as possible all natural and forced frequencies which are to be found in the system. In this direction much can be done to improve the operating stability.

While refinements in the determination of the methods of regulation are desirable, at least for the designer, there is little hope that such refinements may lead to the curing of the intrinsic problems of instability which are characteristic of all dynamic systems in which energy is alternately released and stored and which have several degrees of freedom.

**J. Strasser:** We do not agree with the authors that there should be any difficulty from a theoretical nature when plotting saturation curves at leading power factor. We treated the problem of stability of turbine generators in an article in the *Electric Journal*, August 1926 issue, and used the Potier triangle when plotting the saturation curves and did not have any difficulties. These curves (shown herewith) were obtained by pure theoretical considerations and under the assumption of constant magnetic resistance in any radial direction which can be done in the case of a turbo-generator. The curves obtained by test by Messrs. Douglas and Kane confirm the correctness of our theoretical curves and also our conclusions drawn. We found that of the 0 per cent power-factor leading-current saturation curve the part $C\ F$ corresponds to a slip of one pole and that the slip must occur in the point $C$. This means that for non-salient-pole machines the nose of the 0 power-factor saturation curve shrinks together to a point. For salient-pole machines the slip occurs gradually from 0 deg. at the point $C$ to 180 deg. along the nose and even crosses the 0 field-current line. The authors stated that the nose depends largely on the constant of the tranverse reaction which is in agreement with our conclusions.



We are, however, not of the same opinion as to which is the limit of the stability. This paper seems to base it on regulation and uses the point of change in curvature of the saturation curve at constant power factor and armature amperes as a criterion. This point of minimum field current and constant power factor appears certainly in my curve at leading current only, but what are the limits for lagging current?

Sometimes a high short-circuit ratio of 1.1 or higher is called for and actually we do not need it. We now have generators in operation with a short-circuit ratio as low as 0.75 and we have never experienced any trouble. The power stability depends on the combined characteristics of net work and generator. The only constant is the field current whereas everything else changes. When the system characteristic is known, it has to be superimposed on the generator characteristic at a given excitation and the combined characteristic determined as has been shown in the article in the *Electric Journal*. This will hold for leading as well as for lagging power factors.

**M. W. Smith:** The portion of the Curve $A\ B\ C\ D$ below the point $C$, referred to in Fig. 1 of the paper, is of academic interest only, because it is in the range of instability. It is usually not considered safe practise to operate even salient-pole machines with reversed excitation. However, from a theoretical standpoint, it seems logical that this curve should continue to the point $D$ if an external power factor of 0 per cent leading could be maintained. This requires an infinite capacity with 0 resistance as the point $D$ is approached. The fact that tests have shown a tendency for the curve to approach the point $F$ below the point $C$, simply indicates that 0 per cent power factor is not being maintained. The internal power factor of course, will not be of 0 per cent leading, but will be 0 per cent lagging when zero voltage is reached. The leading-power-factor curve, of course, must reach the point $F$ at zero voltage, because the internal power factor of the machine will be 0 per cent lagging, but whether the leading curve goes to the point $F$ through the point $D$, or some other intermediate point, depends on the power factor of the leading current at the low voltage.

The authors refer to a hope of improved design that will give greater stability under leading-power-factor operation. This condition is hardly one of improved design, but one of special design. Present tendencies in design are towards low cost and high efficiency, which usually result in low gap inductions and high armature reactions. This tendency, of course, is contrary to inherent stability, except as corrected by increased air-gap length. Where leading-power-factor operation is not required, high efficiency and low cost are the important factors. On the other hand, where stability is the paramount consideration, machines of special designs are required. This, however, is a matter of design proportions to meet a special condition, and should not be considered as a general improvement in design, because other factors are usually more important than stable operation at leading power factors. Except in the case of very large high-speed machines, no difficulties have been experienced in the past in producing machines for any desired degree of stability under leading-power-factor operation.

**J. F. H. Douglas:** Mr. Behrend's diagram showing the reversal of the Potier triangle is very interesting. Mr. Behrend makes the statement, that while the parts showing reversed excitation, are not important, yet they can be predicted by the Potier triangle. I don't know whether Mr. Behrend considered the resistance drop in using this, but the diagrams I have seen worked out give this sort of relationship using the Potier method and do not lead to even slight reverse-field excitations, but look like Mr. Strasser's diagram.

The Potier method is inadequate to show that sort of thing, but is an improvement over the A. I. E. E. rule.

I heartily agree with Mr. Behrend and Mr. Newbury as to the question of the effect of relative pole and armature strength.

It was very interesting to note in Mr. Newbury's remarks that approximately double stability was obtained at only a 10 per cent increase in cost. It is to be hoped that by other methods to be developed, the same can be done for less cost.

An intimation was made during the discussion that the Potier triangle is able, so far as regulation is concerned, to duplicate results with quite considerable accuracy. It does not appear, however, that it checks phase displacement with the same accuracy that it checks the voltage-field-current relationship. Inasmuch as the Institute has defined the ratio of torque to phase displacement as a fundamental constant it would be of interest to know whether the Potier method does so check this ratio of torque to phase displacement. So far as the particular machine reported on is concerned, neither the A. I. E. E. method nor the Potier method checks the phase angle as closely as the Blondel method.

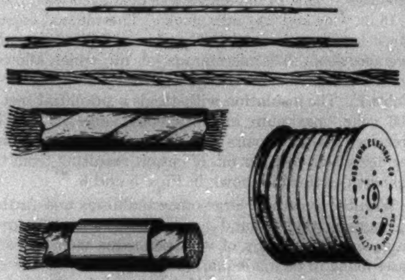
# Recent Developments in the Process of Manufacturing Lead Covered Telephone Cable

BY C. D. HART[1]
Member, A. I. E. E.

THE manufacture of telephone cable consists essentially of insulating copper wire with paper, twisting two insulated wires together to form a pair, again twisting to form a quad if quadded cable is to be made, stranding these pairs or quads into a compact core, removing moisture, covering the core with a continuous sheath of lead or lead alloy, testing the completed cable, and packing it for shipment.

In order to bring out clearly some of the recent developments in manufacturing processes it is necessary to review the beginning of the art.

The idea of using cables for telephonic communication goes back to about 1878. In a talk given in London by Dr. Alexander Graham Bell he stated: "It is conceivable that cables of telephone wires could be laid underground, or suspended overhead, communicating by branch wires with private dwellings, country houses, shops, manufactories, etc., uniting them all through the main cable with a central office where the wires could be connected as desired, establishing direct communication between any two places in the city."



STEPS IN THE MANUFACTURE OF LEAD-COVERED TELEPHONE CABLE

About two years later or in 1880 the idea became a fact and wires enclosed in sheath were used across the Brooklyn Bridge.

The insulation used on these early cables was gutta-percha or rubber but these materials were not very satisfactory for land telephone cables. A little later sisal and cotton were used and the cable core was impregnated to prevent the entrance of moisture and then drawn into successive lengths of lead pipe previously extruded and laid out in straight pieces, the different lengths being then joined together by means of plumber's joints. Impregnation was resorted to because it was difficult to obtain a lead sheath which was entirely free from defects.

By about 1890 paper ribbon had been introduced as a substitute for cotton and similar insulations effecting, of course, a great saving in space and therefore in sheathing material and cost.

FIG. 1—OLD INSULATING DEPARTMENT ABOUT 1892

Fig. 1 shows a group of insulating machines used about 1892. With these machines paper ribbon was wound from a spool mounted eccentrically with the wire and the insulating speed was necessarily very slow.

FIG. 2—OLD TWISTING DEPARTMENT ABOUT 1890

Fig. 2 shows the twisting machines used at that time for twisting pairs. These machines were crude and operated at a low speed.

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[1] Western Electric Co., Kearny, N. J.

*Presented at the Regional Meeting of District No. 5 of the A. I. E. E., Chicago, Ill., Nov. 28-30, 1927.*

Fig. 3 is of an old stranding machine consisting of one drum only as the cable cores were built up one layer at a time and the core was run through the stranding machine as many times as there were layers in the finished core.

The old process of pulling cable core into lead pipe is illustrated in Fig. 4. This picture was posed a few years ago, and the man standing in the foreground was one of a gang who formerly did this work.

FIG. 3—OLD STRANDING DEPARTMENT ABOUT 1890

A forward step in design of insulating equipment was made with the use of pads concentric with the wire which permitted very much higher insulating speeds and very much reduced paper breakage. The twisting machines were also modified to reduce uneven twisting and permit greater speed.

FIG. 4—PULLING CORE INTO LEAD PIPE, METHOD USED PRIOR TO 1894

Another step was the development of multiple drum stranders permitting a number of layers or complete small cables to be made in one operation. Also, extrusion presses were improved so that a continuous sheath of lead alloy could be extruded directly on to the cable core eliminating the pulling in operation.

During the period from about 1900 to about 1920 many changes were made to increase output and improve the quality, also to permit of the use of thinner and narrower insulating papers so that a greater number of pairs of wires could be placed within the same cross-sectional area tending greatly to decrease the cost per circuit.

Cables made about 1888 contained 50 pairs of 18 gage conductor. By about 1902 improvements had been made which permitted 606 pairs of 22 gage wire to be put into a sheath of 2⅝ in. inside diameter which is the maximum size of sheath which has been found generally economical in telephone plants in this country.

By 1912 further improvements in equipment made it possible to use insulating paper of even smaller dimensions and to get 909 pairs of wire into the same diameter of sheath.

On account of increased congestion in the densely populated sections of the larger cities, there was a continued demand for more pairs of wire per cable, and in 1914 the first 1212 pair 24 A. W. gage cables were produced. This 24 gage wire was insulated with paper 5/16 in. wide and 2½ mils thick. The mutual capacitance between the two wires of a pair in this cable averages about .079 microfarads per mi. which allows a normal margin below the guaranteed value shown in Table I. The insulation withstands a potential test of 500 volts (maximum instantaneous value). The increasing number of pairs per cable and the corresponding decreasing cost per mi. of circuit resulting from the changes described is shown in Figs. 5 and 6.

With the growth of large office buildings and further increases in the demand for telephones in the great cities, even 1212 pairs of wire per cable were in some cases found to be inadequate, and in answer to the demand a cable has been developed containing 1818 pairs of 26 A. W. G. wires within a sheath having an inside diameter of 2⅝ in.

These wires are insulated with paper 7/32 in. wide and 1¾ mils thick by the use of specially designed insulating heads and, instead of being stranded in reverse layers as is the case with older types of cables, they are first stranded in groups of 101 pairs, 18 of these groups being then cabled together to form a compact core.

This method of cabling called the "unit" type to distinguish it from the layer type, has several advantages, particularly in splicing in the field. Development work on this 1818 pair cable is not yet complete but there is no reason to doubt that, if there is a demand for a 2400 pair cable, the demand will be met.

For convenient reference Table I has been shown giving the specified limiting characteristics of some of the standard types of non-quadded cables. From the table it will be seen that the larger gage cables are used mostly for trunk work and the smaller gages for connections to subscribers. While the electrical characteristics of these non-quadded cables are of prime importance, they do not demand quite the extreme re-

PRINCIPAL STAGES IN THE DEVELOPMENT ON PAPER INSULATED CABLE.

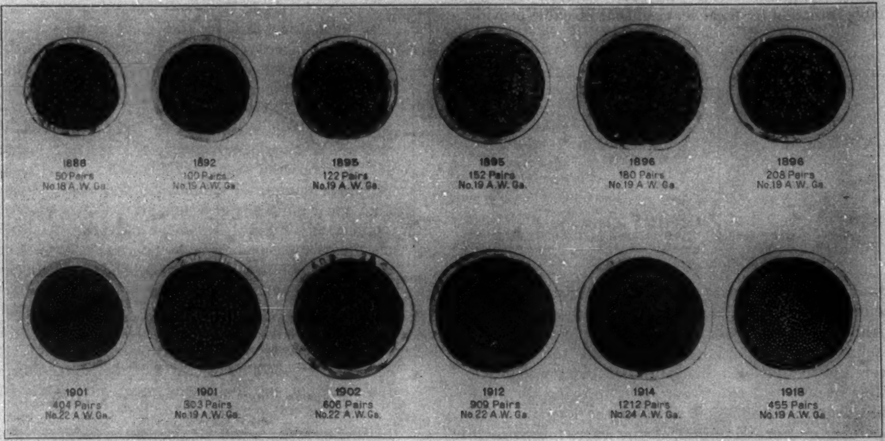
1888
50 Pairs
No.18 A.W.Ga.
1892
100 Pairs
No.19 A.W.Ga.
1895
122 Pairs
No.19 A.W.Ga.
1895
152 Pairs
No.19 A.W.Ga.
1896
180 Pairs
No.19 A.W.Ga.
1896
208 Pairs
No.19 A.W.Ga.
1901
404 Pairs
No.22 A.W.Ga.
1901
303 Pairs
No.19 A.W.Ga.
1902
606 Pairs
No.22 A.W.Ga.
1912
909 Pairs
No.22 A.W.Ga.
1914
1212 Pairs
No.24 A.W.Ga.
1918
455 Pairs
No.19 A.W.Ga.

FIG. 5

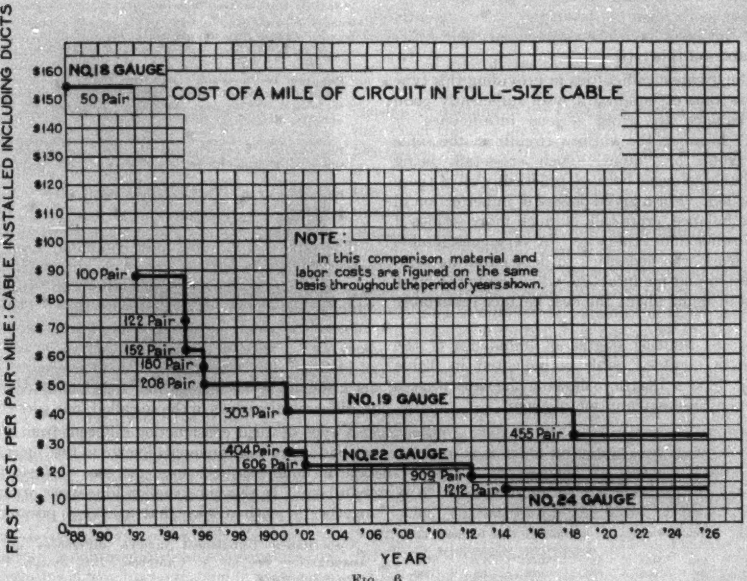

FIG. 6

finement in manufacturing processes required for quadded cables.

The discussion so far has been confined mainly to cable intended for local service, that is, cable providing conductors to connect subscribers directly with the central office and different offices with one another. Gradually, the network of long lines connecting different exchange areas or cities grew and while the early lines were mostly open-wire lines, it was necessary to provide cable in and near the larger cities to bring these lines into the central offices. Most of the long lines were operated on the phantom principle where four wires are combined to provide two ordinary pair circuits and a third or phantom circuit which uses the four wires simultaneously. It was, therefore, necessary to provide cable for these toll entrances which could also be operated on the same phantom principle. More recently many long toll lines have been placed for their entire length in cables of this type.

TABLE I

| A. W. G. | Standard sizes—pairs | Average a-c. capacitance guarantee m. f. per mile | Principle uses |
|---|---|---|---|
| 13 | 11 to 76 | .071 | Toll entrance and long trunks. |
| 16 | 11 " 152 | .071 | |
| 19 | 6 " 455 | .090 | Trunks and long subscriber lines. |
| 22 | 11 " 909 | .089 | Subscriber lines |
| 24 | 11 " 1212 | .085 | Short subscriber lines. |

One of the greatest difficulties in providing this type of cable was that of building it with sufficiently good electrical balance to avoid serious interference or "cross-talk" between the various circuits in the same four-wire group or "quad," such cross-talk being especially liable to occur because practically all of these lines are loaded. For a given degree of imperfection in capacitance balance, cross-talk is much more serious if the line is loaded than otherwise. A very considerable amount of work was necessary to determine the principles of design and manufacture which have the most influence in bringing about the best balance reasonably attainable.

The specified limiting degree of unbalance of the capacitance in quadded cable is indicated in Table II, and Fig. 7 is a diagram showing the capacitances involved and a brief explanation of them.

TABLE II

| Capacitance in m. f. per mile | | Capacitance unbalance in m. m. f. per 500 ft. length | | | | | |
|---|---|---|---|---|---|---|---|
| Pair | Quad | Side to side | | Phanton to side | | Phanton to phantom | |
| Av. | Av. | Av. | Max. | Av. | Max. | Av. | Max. |
| .068 | .112 | 30 | 100 | 120 | 200 | 60 | 600 |

Diagram Showing the Capacities Involved in
Capacity Unbalances between Circuits.

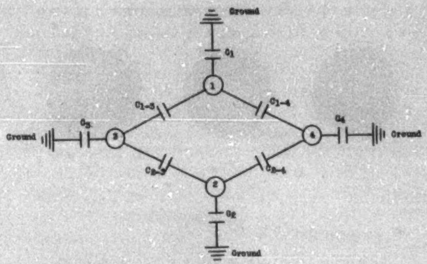

FIG. 7

***Class I Unbalances—Phantom to Side**

1, 2, 3, and 4 represent the four wires of a quad, of which 1 and 2 form one pair and 3 and 4 form the other pair.

Unbalance between Phantom and Side 1-2

$$= 2\,[C_{1-3} + C_{1-4} - (C_{2-3} + C_{2-4})] + G_1 - G_2$$

Unbalance between Phantom and Side 3-4

$$= 2\,[C_{1-3} + C_{2-3} - (C_{1-4} + C_{2-4})] + G_3 - G_4$$

**Class II Unbalances—Side to Side**

1, 2, 3, and 4 represent the same as in Class I Unbalances.

Unbalance between Side 1-2 and Side 3-4

$$= C_{1-4} + C_{2-3} - (C_{1-3} + C_{2-4})$$

**Class III Unbalances—Between Circuits in Different Quads**

Unbalances between two phantoms, or between pairs not in same quad or between a phantom and a pair not in same quad, in each case $= C_{1-4} + C_{2-3} - (C_{1-3} + C_{2-4})$ in which, for

(a) **Phantom to Phantom,** 1 represents the two wires connected in parallel of one pair of a quad, 2 represents the two wires in parallel of the other pair of the quad, and 3 and 4 represent similarly the pairs of another quad.

(b) **Pair to Pair,** 1 and 2 represent the two wires of a pair and 3 and 4, the two wires of another pair not in the same quad.

(c) **Phantom to Pair,** 1 and 2 represent a phantom as in (a) and 3 and 4 a pair as in (b).

The type of quad now most commonly used in toll cables in this country is known as the multiple twin type and consists when completed of two twisted pairs which are again twisted around each other. Differently colored wrappings of cotton around the several pairs hold the two wires of the pair together and afford means of identifying various types of quad and pair as used, for example, in the segregation of the circuits operating in different directions in the so-called four-wire circuits.

A type of quad construction different from that described above and commonly known as the "spiral four" type of quad has been used more extensively abroad than here. In this construction four wires are twisted together in such a way that at every position each wire occupies approximately a corner of a square and the two diagonally opposite conductors are used to form a pair.

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*Capacitance Unbalances involve differences of Direct Capacitances. See G. A. Campbell, *Bell System Technical Journal*, July 1922.

This construction has the merit of very low mutual capacitance of the pairs, but the disadvantage of very high mutual capacitance of the phantom. It has also been found more difficult with this construction to obtain sufficiently good balance to give satisfactory loaded phantom circuits. This type of quad has, therefore, in some cases been used without utilizing the phantom circuits. The loss of these phantom circuits is less than it might seem at first sight because, on account of the inherently lower pair capacitance for a given space per pair, more wires can be placed in the same space for a given capacitance than with other types of construction.

Another characteristic which under certain conditions is important is the alternating current conductance or leakance. The leakance which is measured in micromhos is that property which determines, under given conditions of potential and frequency, the losses in the insulation. These losses become of greater importance when the cable is loaded than when non-loaded and also of relatively greater importance when the conductors are large because then the dielectric losses become relatively greater in comparison with the lower losses in the decreased resistance of the conductor. For this reason many of the large gage loaded toll cables are treated with a special drying process to diminish the leakance.

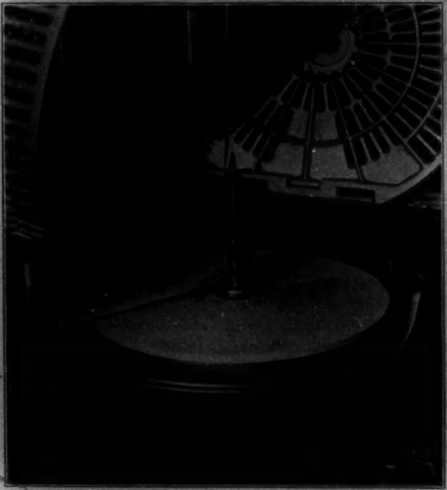

Fig. 8—Paper Insulating Head

Either quadded or non-quadded cable may be used on occasion for crossing rivers, bays, etc., and in these cases the lead covered cable is protected by being first served with two or three layers of jute roving impregnated with tar, then wound with galvanized steel armor wire, and again served with jute yarn, impregnated with an asphalt compound, although in many cases at present this outer serving of yarn is omitted. In case of injury causing an opening in the sheath of such a cable, water may enter the interior and interrupt the service. It is also liable to penetrate for a considerable distance and thus ruin a substantial length of cable which it then becomes necessary to replace. To diminish the amount of cable damaged in this way, this type of cable is sometimes made with a very large amount of paper insulation crowded into a small space to make the cable within the lead pipe very dense. The swelling of this paper as it becomes wet tends to retard the penetration of water and to diminish the amount of cable damaged.

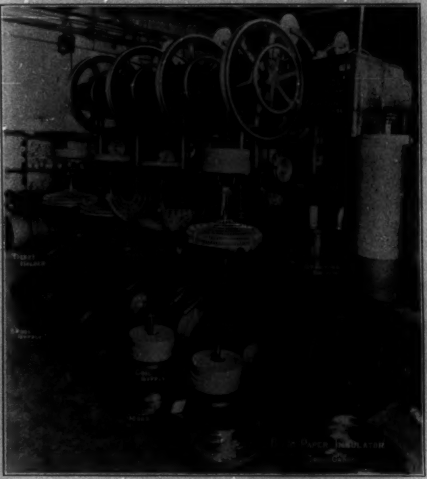

Fig. 9—Heavy Wire Insulator

This dense core construction has, however, the objection that it tends to produce circuits of lower transmission efficiency on account of the higher capacitance and leakance obtained. For this reason cables for this purpose in many cases are made with less dense core construction similar to that used in land cables but with the core treated so as to provide water barriers at frequent intervals to prevent or greatly diminish the passage of water through the barrier, commonly known as a "plug," so that the damage resulting from an injury to the sheath is substantially confined to the portion between two consecutive plugs.

One of the outstanding developments in cable manufacture which occurred about 1911 was the substitution of 1 per cent antimony in lead cable sheath for 3 per cent tin. The use of tin alloyed with lead for cable sheath had been instituted many years before, as it had been found that such sheath was more durable than sheath composed of lead alone and had better mechanical characteristics.

Exhaustive tests showed that lead antimony alloy sheath is equal in quality to lead-tin alloy and, although its use required the development of improved methods of mixing and extrusion, it has resulted in large cost savings.

Another decided improvement introduced later was the substitution of vacuum drying ovens for the old gas or steam heated air ovens. It was found that the drying time using vacuum ovens was reduced to about one-third as compared with hot air ovens together with improved quality and large cost savings.

Before the war the average demand for telephone cable in this country amounted to about 200,000,000 conductor ft. per week. During and after the war this demand steadily increased until now it amounts to about 600,000,000 conductor ft. per week or about 30,000,000,000 ft. per year, requiring annually 40,000 tons of copper wire, 75,000 tons of lead, and 6000 tons of insulating paper.

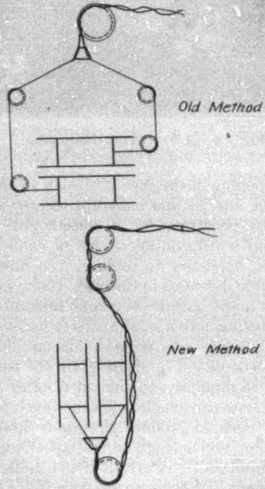

FIG. 10—SCHEMATICS OF OLD AND NEW TYPE TWISTERS

In planning for the manufacture of this quantity of cable, the design of all machinery was reviewed and changes made wherever possible to improve quality or increase output.

A great deal of work was done in improvement of insulating machines, and a ten-head vertical type insulator was developed to replace the older five-head horizontal type for non-quadded light gage wire. In designing the new machine many improvements were incorporated. The old machines had been built to handle relatively strong paper and heavy wires and studies indicated that to insulate finer wires successfully with lighter paper, also to run at high speeds without stretching the wire, and apply a uniform wrapping without backlapping or folding over of the paper and with low breakage per pad the insulators should be rigid, the tension on the wires should be uniform, and both supply and take-up mechanisms should operate smoothly.

Fine Wire Twister
Toll Cable

FIG. 11—COMBINED TWISTING AND QUADDING MACHINE

The relative floor space per head for the 10-head machine including operator's space is about 60 per cent of that taken by the five-head machine but based on production the relative space per unit of production is about 50 per cent. The new machine runs at a head speed of about 3000 rev. per min., carries a 12 in. pad of paper, and in general is a very substantial machine.

The insulating head, the vital part of the insulating machine, has undergone many changes to accommodate the thinner, narrower insulating papers. One of the most important of these has been to improve the tension mechanism which now consists of a very small multiple disk clutch actuated by a system of levers so that a very light but very uniform tension is applied at all times.

This is not only making possible the use of smaller paper ribbon but may permit of changes in the composition of the paper with resultant cost savings. This head is shown in Fig. 8.

Another desirable feature in a paper insulating machine is a bare wire detector as the insulation sometimes parts after passing through the sizing die or polisher as it is called, separates for a few inches and then picks up and goes on. Many electrical devices have been tried and practically all have the objection of high maintenance cost. A very simple and effective remedy was the installation of a second polisher placed between the capstan and take-up spool which catches broken paper and pushes it back until the operator sees and repairs it.

The insulating machine used for heavy gage wire is an 8-head machine built along the same general lines as the 10-head machine. This is illustrated in Fig. 9.

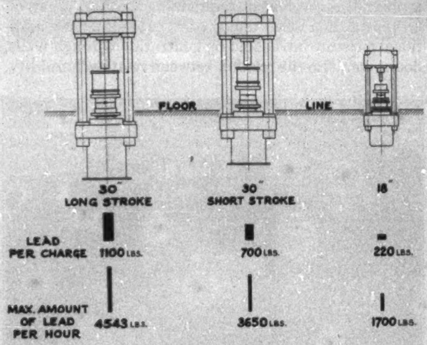

FIG. 12—SCHEMATIC SHOWING RELATIVE INCREASE IN SIZE OF LEAD PRESSES

The method of splicing the copper wire is by means of a transformer, the low-voltage side of which is equipped with clamps for holding the two ends of wire which are butted together, heated by electric current, and brazed by the application of borax flux and silver alloy solder. The transformer windings are so designed with low internal resistance that, although different sizes of wire may be handled, the resistance of the wire between the clamps is so large in proportion to the total resistance that it automatically controls the current and prevents overheating of the wire.

Splices in the insulating paper are made by the application of a thin strip of gummed paper.

New twisting machines for non-quadded light gage wire have been developed and these machines have some unique features which are worth a word of explanation. Fig. 10 shows schematically the old type of twister used ten years ago in which the two spools were placed with axes vertical inside of a flier which carried guide bushings through which the wire from the two spools was brought up to the center of the yoke and to the capstan. These machines operated at 500 rev. per min. and produced one twist per revolution. Assuming a 3 in. twist, the output would be about 125 ft. per min. In the new machines the spools are mounted side by side in a flier, the spools not revolving around each other, with axes horizontal and the wire from each is taken off in a downward direction around a guide pulley and then up through the flier, around another guide pulley and to the capstan. With this arrangement two twists per revolution of the flier are produced and, as the machine is built to operate at 1000 rev. per min., the output for double the speed of the old machine is four times as great or about 500 ft. per min. for a 3 in. twist. Additional features are special tension devices to insure uniform tension on the wire and supports to assist in loading spools of wire into the yoke.

WESTERN ELECTRIC CO.

FIG. 13—ELECTRIC TRACTOR AND TRAILER FOR HANDLING CABLE REELS

The twister for pairing and quadding heavy gage wire in one operation is shown in Fig. 11.

FIG. 14—INSULATING MACHINES

Each spool, containing two conductors, is mounted in a yoke which revolves on its own axis to give the pair twist and the two yokes revolve around each other to give the quad twist. This is accomplished by an arrangement of change gears from which can be obtained practically any length or direction of twist desired.

FIG. 15—TWISTING MACHINES

Modern stranders follow the same general line as the older stranders but the whole design has been reviewed in detail with the view of strengthening and perfecting, and improved tension devices have been developed consisting of a tension arm actuated by the pair which in turn applies a brake to or removes it from the reel head. These are adjusted to give a tension of about three pounds per pair which causes no stretch and prevents over-running. With these, it is possible to run very fine wires at a minimum tension with a maximum smoothness of operation. The drums are gear driven and are capable of running up to 100 rev. per min.

FIG. 16—STRANDING MACHINES

After the cores are stranded, they are dried under vacuum to remove the moisture from the paper and then covered with a lead alloy sheath.

It is necessary after the cable is removed from the vacuum drier to keep it in an atmosphere of a low moisture content until the lead sheath is applied. This was formerly accomplished by placing it in an oven at a temperature of about 160 to 180 deg. fahr. with a resultant relative humidity of not over 10 per cent. Cables maintained at this humidity would pick up very little moisture but in transit from the vacuum drier to the storage oven some moisture might be absorbed; also working in and out of these hot ovens was not particularly pleasant. Therefore, a method was developed for installing the vacuum driers in such a way that one end opens into an enclosed storage area in which the air is maintained at a temperature of about 100 deg. fahr. and a relative humidity of less than 10 per cent until the cables are covered with lead. This temperature and humidity are obtained by cooling the incoming air to a dew point corresponding to the temperature and relative humidity desired and then passing it into the oven. A considerable engineering problem was involved in determining the heat given off by the vacuum driers and the hot cables and the additional moisture introduced by infiltration through walls, doors, etc.; also the relation between relative humidity, moisture content of paper, and electrical characteristics presented a most interesting field for study.

FIG. 17—LEAD PRESS EQUIPMENT

The method outlined above has proved very satisfactory as the cables do not absorb enough moisture to affect their electrical properties and the conditions in the storage area are not unpleasant; in fact, during the summer they are somewhat more agreeable than the outside air during periods of high humidity.

The process of applying lead sheath to cable is one which has not undergone any change in principle since sheath was first applied directly to the cable instead of cable being pulled into it. There has been, however, a number of developments tending to improve the quality or increase the output.

In covering a large cable something more than half of the total time of one cycle of operation is taken up by filling the cylinder with lead and cooling under pressure to the point where it can be extruded. The tendency, therefore, has been to build presses with larger lead containers in order to increase the time of extrusion relative to the total cycles.

The diagram (Fig. 12) shows schematically an early type of press, one which was considered standard a few years ago, and one of the presses designed and built recently. Underneath each press is a figure showing the lead content per charge and the relative amount of lead extruded per hour by each of the three presses.

Fig. 18—General View of Reel Yards

As will have been noted from the diagram, the stroke of the newest type of presses is about one foot longer than that of the former presses although the diameter of the lead container and the diameter of the water ram are the same.

The pressure for operating these presses is furnished by a hydraulic pump, pumping water at six thousand lbs. pressure per sq. in. Presses were formerly connected to four plunger vertical type pumps, but it was found that more water could be used with the large sizes of cable and, therefore, new pumps were built with six plungers, giving a proportionally greater output. The diameter of the lead ram is one-third that of the water ram so the pressure on the lead during extrusion is about 54,000 lbs. per sq. in.

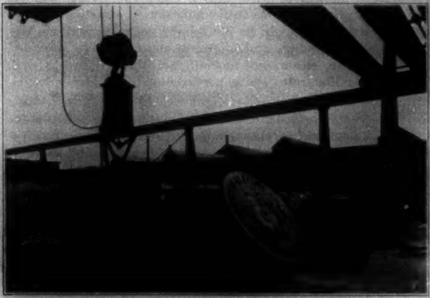

Fig. 19—Delivery of Empty Reels from Yard

Aside from increasing output many studies have been made to determine the exact mechanism of lead extrusion, the relative flow of lead in different parts of the extrusion block, the effect of application of heat at different points, etc.

An interesting experiment consisted in filling an extrusion block, with layers of different colored waxes and noting their flow under pressure. This gave valuable data as to the proper contour of the extrusion chamber.

The concentricity of sheath is affected not only by the contour of the extrusion chamber but also by the manner in which heat is applied; and thickness is affected by temperature and speed of extrusion so that the human element is an important factor, and it is necessary to have thoroughly trained and reliable operators on this kind of work. Temperature indicators are used to show die block temperatures and the temperature of the molten lead is automatically controlled and recorded.

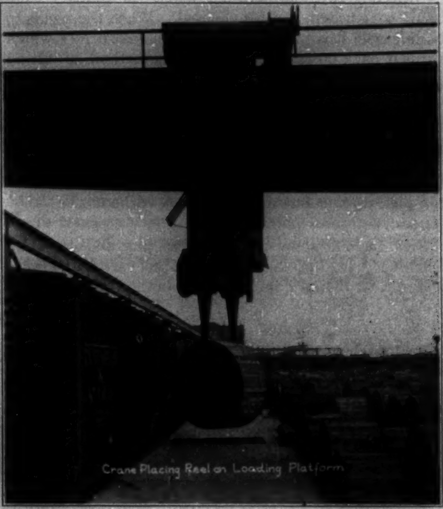

Fig. 20—Crane Placing Reels on Loading Platform

Handling of lead-covered cable on reels, the total weight of which runs from one to five tons, is a very distinct problem. This handling from press to test is done by a crane which picks up the reels and carries them to the place where they are to be tested for insulation resistance, capacitance, dielectric strength, etc.

After the cables are tested, the ends are sealed and wooden lags are fastened around the periphery of the reels after which the cables are taken to a storage yard until the customer's order is completed at which time they are shipped. A special tractor and trailer, Fig. 13, has been developed and substituted for manual handling.

Handling cables from the reel yard to the loading platform was a very serious problem particularly in the winter during snow storms. This was taken care of by the installation of overhead cranes for picking up reels and placing them on the platform.

The lifting mechanism for empty reels consists of a solenoid operated plunger controlled by the crane operator. The reels are turned on the side, the plunger inserted in the bushing and the operation of the solenoid throws out two lugs which prevent the plunger from being withdrawn, and lift the reel. When the reel is to be released, it is put down on an inclined surface which turns it back on to its flanges. This method of lifting empty reels permits them to be stacked one on top of the other and saves storage space.

The lifting mechanism for full reels consists of two side arms with lugs, moved horizontally by means of a double-threaded screw and a motor controlled by the crane operator. With this device the crane operator can pick up and put down any reel without the assistance of a ground man.

Figs. 14 to 20 show insulating, twisting, and stranding machinery, lead presses, and cable reel yard with cranes and special lifting equipment for both empty and full reels.

The methods of cable manufacture are ever changing. What has been described as strictly up to date today will, doubtless, on account of new developments be superseded by new methods, new equipment, and new designs so that the cable plant of the future will be different from and more efficient than that of the present.

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## Discussion

**E. O. Neubauer:** Mr. Hart, in his paper, has called attention to the progress in the manufacture of non-quad cable. The large increase in the number of pairs placed in a single sheath was due in part to improved manufacturing methods, but was largely due to a gradual decrease in the size of conductors and the thickness of the insulation used. This resulted in the manufacture of cables having considerably higher transmission equivalents than the early cables which were mostly large gage. The transmission equivalent of a 26-gage cable, for example, is about 1½ transmission units higher than that of an 18-gage circuit.

The non-quad cables are used mostly for exchange distribution, that is, to connect subscribers' stations with the central office and to connect central office and office exchanges. The increased transmission losses were necessarily met by improvements in developments in other parts of the telephone plant. In the case of subscribers' lines, the increased transmission losses were met by improvements in the transmitter, receiver, and induction coil of the telephone, so that today a 24-gage circuit with the improved instruments will give as good transmission as an 18-gage circuit with the instruments formerly in use.

One of the diagrams of Mr. Hart showed the gradual decrease in the cost per pair of cable between 1888 and the present time.

One of the most important items in the cost of outside plant facilities is conduit. In Chicago the cost of conduit is about $4000 per duct including a proportional part of the associated manholes. This one item alone is considerable when it is remembered that in 1888, 36 ducts were necessary to serve the number of subscribers served today with one duct.

The introduction of loading has made possible the use of small-gage cables to connect two offices in an exchange area. A trunk connecting two offices, say 20 mi. apart, could employ 22-gage conductors properly loaded whereas if the loading were not available it would be necessary to use 16-gage conductors which would reduce the number of pairs available from 900 to 150.

Quadded cables are manufactured in the so-called large gages, that is, the 13-, 16-, and 19-gage conductors and the insulation is somewhat heavier than in the smaller gages. The wires are also placed more loosely within the sheath. The result is that the transmission equivalents obtained with quadded conductors are somewhat better than with non-quadded conductors. The reason for this is that quadded cables are used for toll service mostly, which means that they have longer distances to span than the non-quadded cables. This makes it necessary to obtain cables of a smaller transmission equivalent per mile than the non-quadded cables. Even with the use of larger gages it is also necessary to employ amplifiers where the length of circuit exceeds about 80 mi.

**H. P. Charlesworth:** Possibly a few operating considerations might be of interest.

When we consider that today we are requiring for the telephone companies of the Bell system, more than 30,000,000,000 conductor-ft. of telephone cable each year we see how important these various developments which have been discussed really are in the daily operation. The fact that we can now get 1200 and 1800 pairs of wires in these cables is interesting because it is hard to realize how we could possibly serve our large communities without developments of this kind permitting us to get a large number of wires into a building. Again, without this large number of wires in a single sheath our streets in the downtown sections would be pretty well occupied with nothing but telephone conduit, and of course space must be provided for the electric, steam, gas, and all the other utilities as well. That further illustrates the importance of these developments.

Another interesting matter might well be mentioned relative to the toll-cable problem. That program and the extension of toll cables has gone on throughout the country in the last few years on a very large scale. Today we have an all-cable route all the way from Boston through to St. Louis with various branches bringing in a very large number of cities on a cable basis.

These cables require, as one of the speakers mentioned, amplifiers at about every 50 mi. for the longer lines and the circuits are operated for those long distances on what is called a four-wire basis. That is, the voice coming from New York to Chicago goes on one pair of 19-gage conductors and back on another pair with amplifiers in each of the circuits. That permits a more stable and more satisfactory operating circuit. Then at the terminals these pairs are brought together, of course, into the usual two-wire circuits to permit of connection through the switchboard to the ordinary subscriber's line. The loss, to start with, is of course enormous and the amplification has to be perfectly enormous, something like $10^{45}$ to make up for the enormous loss and to give a margin for satisfactory transmission.

Under those circumstances a relatively very small change in the temperature conditions of cable, whether in the aerial or underground portions, would have a very definite and very decided effect on the attenuation so that it is necessary to regulate that, and this is accomplished by means of having a pilot wire, so-called, in the cable associated with certain automatic control apparatus so that as the wire changes in temperature you have automatic regulation of various amplifiers along the cable thus maintaining a stable and definite net over-all efficiency.

The cable program is extending now up toward Minneapolis and before long will be down toward Atlanta in the South, up and down the Pacific Coast in certain sections, particularly between San Francisco and Los Angeles. A second route has already been provided from the East around through Buffalo meeting the other cable at Cleveland.

**C. D. Hart:** The only thought I should like to add is that the discussion has tended to make apparent the need for great care in manufacturing cables, particularly quadded cables, and has broadened the picture to include not only the manufacture of cable but its place in the general communications plan.

# Telephone Toll Plant in the Chicago Region

BY BURKE SMITH[1] and G. B. WEST[2]
Associate, A. I. E. E. Non-member

***Synopsis.**—This paper described the telephone toll system in the region within a radius of about 50 mi. from Chicago. In this system have been established 21 toll centers at which are handled the toll traffic of their own exchanges and 95 other exchanges in the area. Descriptions are given of the toll plan and the toll plant, methods of handling toll calls, volume of traffic handled, etc. A most important consideration is the very rapid growth taking place in toll-service requirements in this region.*

COOK County and its seven adjacent counties in Illinois, and two in Indiana, together form the metropolitan area which is referred to in this paper as the "Chicago Region." Within this area there are about three and one-quarter million people in Chicago proper, with another one and one-quarter million distributed in about one hundred communities in proportionately decreasing densities from the Chicago city limits to the outer boundaries about fifty miles distant. The growth of the population in this area is at the rate of approximately a million per decade.

This area is served telephonically through local exchanges which are, for the most part, identical with the one hundred odd communities already referred to, and each receives service within its area under its local service tariffs. Between any one community and any other community, service is, in general, subject to an additional tariff or toll charge based on the center to center distance.

The general advancement of this region has been material. This has been more than reflected in the accompanying increase in telephone business. Within this business the rapidity of increase has been even more marked in the toll than in the local phase. Since all indications point to a continuance in this same relative progress, it may be appreciated that the toll development will present a continuing problem if no other factor than magnitude alone need be considered. Along with magnitude, however, there are problems of re-alinements of distribution as communities of interest and methods of operation change and plant design advances.

It is obviously as impractical to provide each local exchange with direct or fixed connections to every other exchange as it is to so deal with the various subscribers' stations within a local exchange. Switching or distribution centers must, therefore, be arranged which result in greater toll plant efficiencies and toll line route concentrations. The actual result of this in the Chicago region has been the establishment of 21 toll centers, at which are handled the toll traffic of their own exchanges and the other 95 exchanges in the area. These 95 exchanges have therefore become, for toll purposes, satellites to these centers, or as it is generally expressed, "tributary exchanges." It is expected that these 21 centers may be still further reduced with improvements in methods and plant design.

Toll traffic between these toll centers, whether originating at the centers or at their tributaries, is handled by one of three operating methods known respectively as:

1. *The Toll Board Method*, in which the calling subscriber is connected with the recording operator, familiarly known as "Toll" or "Long Distance." At the present time the recorder takes the details of the call and dismisses the subscriber until a line operator can complete the call. This method is now undergoing a change. As soon as equipment rearrangements are available the work of the recording and line operators will be combined and marked service improvement effected.

2. *Two-Number Toll Board Method*, in which the "A" operator accepts the call and passes it to a "Toll Board" operator, who handles the call while the calling subscriber remains at his telephone. This method will tend to merge with the improved toll board method.

3. *A-B Toll Method*, in which the "A" or subscriber's operator, on receiving a call from the subscriber, supervises the call through to the called station, the calling subscriber staying at the telephone.

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Under the last two methods, only calls made for a station by number can be completed, and the first method is used for all calls on which a particular person is asked for. The determination of the proper use of each of these three methods involves consideration of service requirements and economies. In general, the so-called A-B method is used for short-haul traffic of large volume, the two-number toll board method for short and intermediate distances of lesser volume, and the toll board method for long-haul traffic of small volume. These, of course, are only general groupings, and the method adopted in any individual case is based on the actual conditions to be met.

There are also, of course, variations within these methods, such as, for example, the use of a tandem switching center in an A-B method. This variation as applied to Chicago, consists of a tandem board at which are centered toll trunks from Chicago exchanges as well as from outlying exchanges. Calls received by the "A" operator at a Chicago exchange, for one of these outlying exchanges, may be routed via the tandem switching operator, who in turn connects through to the called office, via the toll trunks available to her. In this way it is not necessary to have direct toll lines from every local board in the area to every other local board; yet, at the same time, it is possible to complete these calls by the A-B method. There is at present only one tandem board in the Chicago region, and this is located in the loop district. Of course, as the volume of traffic between any two exchanges, which is handled through the tandem board, increases sufficiently to make it economical, direct toll circuits between the two exchanges are provided.

Progress in the Chicago region has been steadily changing from a condition of practically all toll board operation with the hang-up method, to two-number and A-B toll methods without hang-up as the toll volumes have increased and station-to-station service has become more popular until today fully 87 per cent of the Chicago regional toll traffic is handled by the A-B method. The improved toll board method will further increase the percentage of business handled on a "no hang-up" basis.

In this connection, it should be noted that concurrently with this change from toll board to A-B operation has come a marked change in speed of service. The average speed of service, that is, the average time from the request for a number by the calling subscriber to the ringing of the bell of the called subscriber, under the toll board method, averaged about seven min., while the speed of service under the two-number and A-B methods averages less than one min. Part of this reduction in time of connection is, of course, a direct result of the methods of operation, although part of it is also a result of the more liberal provision of facilities. However, such provision to permit of faster service has resulted in stimulating the use of the toll service, with a corresponding increase in the size of circuit groups and in the efficiency and speed with which these circuit groups can handle the traffic.

Associated with this regional toll traffic, there is the traffic which goes out of the area to more distant points, and that which comes into the area from distant points including traffic to and from such points which must be switched at a center, like Chicago. The economical provision of the plant to care for this extra regional traffic, with that for the short-haul traffic, further adds to the complexity of the plant design.

The provision of the plant for this intra- and extra-regional traffic to be economically carried out must be based on some general plan of future development within the area. Such a plan, generally known as the "toll fundamental plan," projects volumes of traffic, anticipates methods of handling, and arranges toll centering, tributary, and route layouts for some ultimate period, normally about 20 years in advance. Such a plan must, of necessity, be reviewed and revised from time to time to keep pace with the developments and changes in toll service requirements, and is a guide to current toll plant construction rather than an absolute control of it.

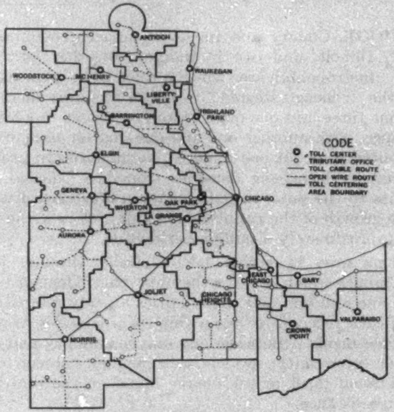

FIG. 1—TOLL FUNDAMENTAL PLAN

Illustrations of some of the problems of growth and development of toll plant within the Chicago region follow:

Referring first to the toll fundamental plan, Fig. 1 shows the grouping of the exchanges in the Chicago region around the toll centers. For example, the small exchanges around Joliet under this plan reach Chicago and other points via Joliet. This figure incidentally indicates the several toll routes radiating from Chicago, such as the route along the North Shore, that northwest from Chicago toward Barrington, another directly west through Oak Park and Geneva, and the one southwest toward Aurora with a branch toward Joliet and Morris; still another directly south to Chicago Heights, and one southeast to East Chicago which forms part of the main route to points East, including New York.

Considering now the growth in toll traffic in this region, there were ten years ago approximately 560,000 telephones with approximately 11,600,000 toll messages per year. In this same area, with something over one-million telephones, we are now handling approximately 46,000,000 toll messages per year, or an increase of 300 per cent, while the number of telephones has increased only 90 per cent, and the population approximately 33 per cent. These relations are shown diagramatically in Figs. 2 and 3.

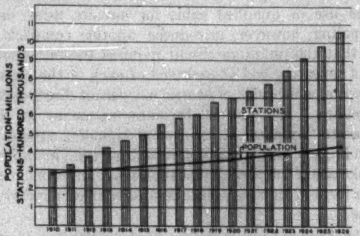

Fig. 2—Total Stations and Population in Chicago Region

While a large part of this increase in toll traffic is within a 50-mi. radius of Chicago, yet the longer haul has increased greatly, as for example, between Chicago and St. Louis, 185 messages per day ten years ago, compared with 650 messages today; between Chicago and Detroit, 180 messages per day ten years ago compared with 1000 messages today.

Toll cable has been the solution of the increasing toll circuit requirements, since there is a definite limit to the number of circuits which can be provided by open wire.

Notwithstanding the continued use of open wire on the less dense routes, the extension of cable has decreased the toll open wire in the plant. This is shown in Fig. 5. It will be noted that cable wire mileage has increased from 36,000 in 1916 to 224,000 in 1926, an increase of 520 per cent in 10 years, while toll aerial wire mileage in this region has decreased somewhat during this period.

The rapid extension of the toll cable plant is shown in Fig. 4 on which is indicated the cable in service five years ago, the cable now in service, and that rather definitely foreseen within the next five years. It should be noted that in several of the routes shown a second cable, and in some cases a third and fourth cable, has been placed.

In designing such a cable network as this, there are a great many problems which must be solved before the plant can actually be provided; *e. g.*, starting out with an assumed grade of transmission, which it is necessary to provide from any station to any other station, the distribution of the losses must be economically apportioned. Take the simplest case of toll connection, consisting of a calling subscriber's loop, the called subscriber's loop, and the connecting toll circuit. Probably it would be possible to apportion 45 per cent of the loss to each subscriber's loop, and design the transmission of the toll circuit so that only the remaining 10 per cent would be in that portion of the connection. Or it would also probably be possible to assign 10 per cent of the loss to each subscriber's loop, and take up the remaining 80 per cent in the toll circuit. There is, of course, an economical division of these losses, and these must be determined in designing the toll plant.

Consider the design of the tandem trunk plant. These trunks may be classified into two groups, those connecting the tandem board with city offices, and those connecting the tandem board with suburban offices. If we should divide the total allowable line loss between these two groups equally, we would not obtain an economical balance, since the tandem trunk which is extended into suburban territory may be as much as fifty mi. in length, while the city tandem trunk will be very much shorter. There is, therefore, a very material saving by dividing the allowable losses unequally between these two classes of tandem trunks. In Chicago a study of the costs involved showed that this division of losses should be made up as follows:

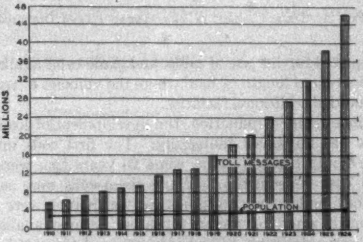

Fig. 3—Total Toll Messages and Population in Chicago Region

Tandem trunks in the metropolitan zone (within the city limits principally) ...................... 5.0 Transmission units[3] allowable loss.

Tandem trunks within the suburban zone..........10.4 Transmission units allowable loss.

In the earlier days of the telephone business, all toll circuits of any appreciable length were provided by bare wire strung on insulators, and it was not until a relatively few years ago that the development of the art permitted the use of cable circuits for this purpose. The earlier toll cables consisted simply of insulated wires, twisted in pairs. In this period transmission losses were so large that this type of cable could only be used for short distances, even though consisting of 13 and 10 gage wire.

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[3] For description see paper by W. H. Martin, A. I. E. E. Trans., Vol. 43, 1924, p. 797.

The development of the loading coil, which has been described in other papers presented before the Institute, permitted further use of cable, and made cable available for increased length of haul where the volumes of traffic demanded additional facilities.

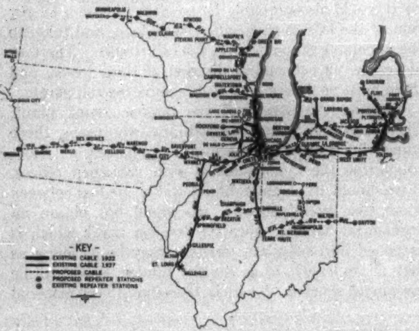

Fig. 4—Toll Cables in the Great Lakes District

Since their introduction, the development of loading coils has advanced materially. The first coils introduced into the toll plant, some 25 years ago, were of iron core construction. While these coils were satisfactory under the conditions for which they were developed, when telephone repeaters became available it became desirable to provide improved types of loading coils. A loading coil having a pressed powdered iron core was, therefore, made available. The outstanding advantages of this coil was its higher magnetic stability and the smoother impedance conditions on the lines resulting from its use.

This coil has proven satisfactory for repeatered circuits. It is now being superseded for new construction, however, by a new type of coil having a pressed powdered permalloy core. This new core material permits a large reduction in the size of the coils without degrading established efficiency standards, and will result in large plant economies. Fig. 6 shows the relation of size of pots required to incase a given number of the new and old coils. This reduction in size is of great advantage where such coils must be placed in underground systems in congested city streets, or where in the country it is desirable to place them on pole fixtures.

Another development in the cable art is that of quadded cable. In this type of cable two pairs of wires, each constituting a circuit, are twisted together to form what is known as a "quad," and these quads may be used to provide a phantom circuit, thereby increasing the message capacity of the cable by 50 per cent. While this plan of making available a phantom circuit had previously been used in the open wire plant, it was not until quadded cable was developed that the phantom was available in cable circuits. The use of quadded cable for circuits using direct signaling, however, introduced another complication, in that the phantom circuit requires the introduction of a repeating coil at each end of each of the physical circuits, which will, of course, not permit direct-current signaling. It therefore becomes necessary in these cases to "by-pass" direct-current signaling around the windings of the phantom repeating coil, in order to make use of the phantom possibility. The economics of this form of signaling must be studied in each individual case.

Another important factor in the extension of cable for toll purposes is its immunity from storm damage. As is well known, open wire is subject to very serious breaks in the sleet storm area, while cable is practically immune from damage in such storms. It is estimated that to make an open wire line strong enough to give a strength of construction comparable to that obtained with aerial cable would require very large poles on very-short spacing or other special construction. Such a line also would need at least No. 8 B.W.G. hard-drawn copper wires. It is not certain that even such a line would stand up under severe storm conditions. Aerial cable construction on the other hand has been in use long enough to indicate that construction will almost never go down during the severest storms. In the extreme cases in which a break does occur the circuits in the cable probably will continue to give service. An example of how modern toll cable construction enables service to be given even if the poles are broken

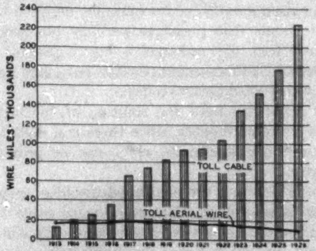

Fig. 5—Toll Cable Wire and Aerial Wire Mileage in the Chicago Region

and the cable is thrown to the ground was shown in the case of a cable pole line between Maywood and Elmhurst, suburbs of Chicago. This line which was blown down in May 1927, during a wind storm of great severity carried two toll cables and also a subscribers cable. Although over a mile of pole line was blown down, the only trouble which occurred was due to a crack in the sheath at a splice which resulted in nine pairs being temporarily out of service out of a total of 845 pairs in the two toll cables.

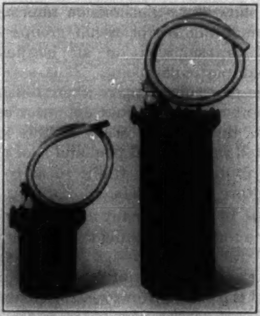

Fig. 6—Comparative Size of Loading Coil Cases

Each case containing 200 loading coils:
Left—Permalloy Core Coils—Weight 725 pounds
Right—Iron Core Coils —Weight 1750 pounds

Cable plant must of necessity be added in rather large units with fairly large margins over immediate requirements. If future requirements are overestimated, this will result in an appreciable amount of idle plant investment, or if underestimated, uneconomical reenforcement or replacement becomes necessary. The provision of cable thus requires careful forecasts for long periods as to the probable traffic volumes and circuit requirements.

Even with the developments in cable and loading coils, which are discussed previously, the distance to which cable could be extended for toll purposes was limited, and it was necessary to use No. 13, and in some cases No. 10, gage conductors to meet transmission requirements. With the development of vacuum tube repeaters[4] and their availability for use with toll cable, the distances to which such cable could be economically extended was increased very greatly. Furthermore, as a result of the use of repeaters, it has been possible to reduce the gage of cable circuits, so that modern toll cables now seldom contain conductors larger than No. 16 gage, and the greater proportion of conductors in such cables is generally No. 19 gage.

The first installation of vacuum tube type repeaters in the Chicago region was in 1914 in connection with the transcontinental line. This was a small installation, and growth in repeaters in this territory continued at a fairly slow rate up to about 1924. This slow growth was due to the fact that it had been necessary to install practically no long toll cables other than that extending between Chicago and Milwaukee. Beginning with the year 1924, toll cable was rapidly extended in various directions from Chicago for distances of over 100 mi. The Chicago-New York cable, for example, was completed in 1925, and the Chicago-St. Louis cable, which lies almost entirely within the State of Illinois, was completed in 1926.

At the present time, there are approximately 750 repeaters in use in the territory of the Illinois Bell Company, a very large proportion of which is in the Chicago region. Fig. 7 shows the location of repeaters in this Chicago region.

Another problem which has come up in recent years, although not expected to be a recurring problem, is concerned with the quality of transmission. When toll circuits consist of only non-loaded open wire, the effect of the line on intelligibility is negligible, as circuits of this type are very nearly distortionless. The introduction of loading into the telephone plant, however, has brought with it a certain amount of restriction of the range of frequencies transmitted, varying in degree with different types of circuits. It is well known that loading has the property of cutting off or suppressing frequencies above a certain number of cycles, depending on the character of the loading.[5] One of the fundamental questions of loading has been to determine

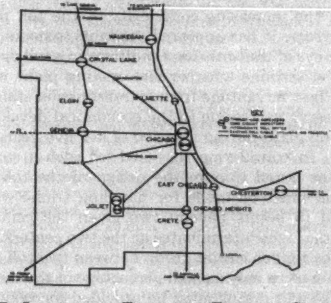

Fig. 7—Location of Telephone Repeater Stations and Their Relation to the Toll Cable Network in the Chicago Suburban Area

what range of frequencies should be transmitted to furnish a satisfactory grade of speech without undue distortion. Early studies indicated that a cutoff frequency of about 2300 cycles would be satisfactory. These studies were based on measurements made by ear methods, however, and have been supplanted by more recent studies made by more scientific means. These studies show that it is economically practicable and desirable to set a limit of 2800 cycles as the minimum cut-off frequency in loaded cables, and accordingly all new toll plant is now designed on a basis of a cut-off frequency of 2800 cycles or better.

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[4] See paper on *Telephone Repeaters*, by B. Gherardi and F. B. Jewett, Trans. A. I. E. E., Vol. 38, 1919, p. 1287. Also by A. B. Clark on *Telephone Transmission on Long Cable Circuits*, Trans. A. I. E. E., Vol. 42, 1923, p. 86.

[5] See paper on *Development and Application of Loading for Telephone Circuits*, by Thomas Shaw and William Fondiller, Trans. A. I. E. E., Vol. 45, 1926, p. 268.

In Chicago, at the time the decision was made to adopt a higher cut-off frequency, there were installed about 50,000 loading coils in the local trunk plant. Many of these were on trunks which are used on toll connections, such as direct A-B and tandem trunks and toll switching trunks. These trunks had a cut-off frequency of 2300 cycles. A study of the Chicago city trunk plant showed that it was economically desirable to change the spacing of coils so as to raise the cut-off to 2800 cycles or better, and this work has now been practically completed so that all toll calls, with the exception of those involving a few circuits in some of the first toll cables installed, are now routed over trunks having the high cut-off features. As a net result of this increase in the cut-off frequency, a lower volume equivalent can be used, which means that a given type of loaded circuit can be used for a somewhat longer haul than if the cut-off were lower.

With the increasing complexity of the toll plant in recent years, it has appeared desirable to make periodical surveys of transmission conditions in a toll operating area to determine whether the existing plant is being used to best advantage from a transmission standpoint and to serve as a guide to the economical development of the toll plant during a period of say five years in the future. In considering the need for such a survey it should be noted that in the design of the toll plant, provision must be made for handling traffic which is switched to points beyond two given toll centers, as well as that which terminates at the two centers. This traffic for a given circuit group between two toll centers may amount to only a small percentage of the terminating traffic and means must be provided for taking care of transmission on such business which will not react seriously on the cost of providing facilities suitable for terminating business. Adequate transmission on switched calls may often be provided economically by the installation of repeaters[3] or by setting aside a certain proportion of circuits in a given circuit group for use in switched business and designing those circuits so they will be of a high enough grade to be used for either switched or terminating business. The economical location of repeater points and determination of the proper balance between circuits designed for terminating business and those designed for switched business can best be decided by a comprehensive study of transmission conditions for the entire area.

In making a transmission survey, an analysis of toll traffic is prepared covering the whole area for a representative month, showing both terminating and switched traffic and indicating the present transmission conditions as compared to the transmission objectives which have been established. By dividing the territory into natural subdivisions such that the traffic for different parts of the territory passes through a relatively small number of main switching points, it is often found that the analysis at a particular switching point will show that transmission improvement of a relatively small number of circuit groups will provide satisfactory transmission on all business switched through that particular point. It is also possible to pick out the particular centers where toll transmission under present conditions does not meet assumed objectives. A transmission study of this kind supplements the toll fundamental plan and is of assistance in the proper routing of toll traffic so as to fit in with expected future toll projects.

There are, of course, many other problems in the design of the toll plant relating not only to what might be termed transmission design but also methods of construction and problems of economics entering into the design of the plant. However, the greatest problem, as indicated in the earlier part of the paper, probably is that brought about by the extremely rapid growth taking place in the toll service requirements of the Chicago region.

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## Discussion

**G. S. Dring:** The importance of an equitable division of transmission losses in the trunk, substation, and toll-line facilities is stressed in this paper. Not only must the transmission of each unit be within the required limits, but the over-all transmission of the various units when connected together to form a toll circuit from subscriber to subscriber must be such as to provide a satisfactory talking channel from the subscriber's point of view.

This paper brings out the advantages from a service and maintenance standpoint of toll cable over open wire. It should be kept in mind, however, that while the use of toll cable does stabilize the service rendered over it, constant care must be exercised from the time it is installed and throughout its life to insure that the conductors are at all times in proper electrical and physical condition. Experience has taught that if we expect to make use of the phantom possibilities and avoid crosstalk from one pair to some other pair of phantom, we must make careful capacity-balance tests on the pairs of the various sections of cable before connecting them together, having in mind the desirability of keeping the unbalance between the various pairs and within quads to a minimum on the finished over-all cable. Further, the lead sheath must be kept air-tight or low insulation will result. Pressure tests by means of nitrogen or carbon-dioxide gas are made on sections of the cable before splicing is completed and thus any leaks or openings are located. After the cable is placed in service, insulation tests are made daily to insure that cracks or other openings have not occurred in the sheath.

Temperature also is a factor which must be compensated for, as an increase in temperature causes an increase in resistance of copper conductors thereby increasing the transmission loss for a given section. The longer aerial toll cables are divided into regulator sections of approximately 170 mi. each.

Transmission regulation made necessary on account of temperature changes is accomplished automatically by a wheatstone-bridge arrangement having for one arm a pair in the cable. A change in temperature affects this pair as it does the other pairs in service and the change in the regulator-pair resistance controls relays which increase or decrease the gain of the telephone repeaters associated with the working toll circuits at the regulator stations and thus compensate for increases and decreases respectively in temperature.

Signaling over long toll circuits is a subject in itself. Mr. Smith points out that the phantom coil does not permit d-c. signaling. The superimposing of d-c. telegraph circuits on toll circuits also makes d-c. signaling impracticable. The use of 135-cycle ringing current has been used on composited telephone circuits for a number of years and recently the use of 1000-cycle ringing current has been introduced over the longer-toll circuits. The 1000-cycle cycle ringing current has the advantage of being efficiently transmitted over telephone circuits as it is within the speech range.

**H. S. Osborne:** The extremely high losses in very long toll cable circuits have been referred to. These long toll cable circuits are made of copper totalling about 0.1 in weight the open-wire circuits which they displace, and the amount of loss per unit length is larger in an even greater proportion. Taking the cable circuits themselves, the loss of energy per unit length is 30 or 40 times as great as it is in large-gage, open-wire circuits. Whereas with ordinary terminal losses one could talk perhaps 400 mi. effectively on the open-wire circuits, the corresponding limit for these small cable wires would be 10 or 12 mi. Now, by the loading, which is discussed by Mr. Smith, that is raised to perhaps 50 mi., and then by the use of amplifiers the limit is very greatly extended.

The provision of proper energy efficiency is, however, only one of the electrical problems involved in establishing these circuits. Another one of great interest is the limitation of the distortion of speech. In order for the speech to remain clear it is necessary that the electrical efficiency of the circuit be very uniform over a relatively wide range of frequencies, about 200 to 2500 cycles. Bearing in mind that the loss of energy in a circuit from New York to Chicago is $10^{46}$, it is evident that the regulation of that loss to a very uniform figure over a wide range of frequencies presents a very formidable problem. It has been necessary not only to make the cable circuits themselves as nearly distortionless as possible, but to compensate for the remaining distortion by compensating devices installed in connection with the repeaters.

These very long circuits have some extremely interesting transient current characteristics. The voice currents, as you know, consist of a series of discontinuous groups of high-frequency oscillations, and the impinging of these oscillations on the long cable circuits produces very important transient currents which it has been necessary to eliminate by attention to the method of design of the cable. These transient currents depend on the electrical constants of the cable itself.

Then there is another kind of transient current arising from the fact that the speed of propagation of the impulses is not infinite and, in fact, on the loaded cable circuits of a type used very widely, the velocity is about 12,000 mi. a second. At the distant end there is always a very considerable reflection of current because of an irregularity in the impedance of the circuit so that if such a circuit were to be used between New York and Chicago, the reflected current would come back after traveling 2000 mi. with a time lag of about $^1/_6$ sec., and on such a circuit one would hear the words coming back as a very distinct echo which is extremely annoying.

It has been necessary to do two things to reduce those echoes on the very long circuits. One is to design circuits with a higher velocity of propagation. The velocity on the circuits actually used between New York and Chicago is about 25,000 mi. a second. Another thing has been to make use of the voice currents themselves to suppress these so-called echo currents. That is done by having the voice currents operate a relay to short circuit the return path, and the time lag in the echo is sufficient to permit that operation to take place and cut off the echo currents before they have time to return.

Another very important series of problems, which constitutes a story in itself, is that of preventing interference between the circuits in the same sheath. In a toll cable there are on the average perhaps 250 independent circuits within a diameter of 2.5 in. To prevent those circuits from producing interference with each other, particularly where we are dealing with very great lengths and extreme ranges of energy input and output, has constituted an interesting and important series of problems.

As a final word, I should like to ask you to bear in mind that these circuits must be so designed and constructed that it is practical to maintain them without excessive expense. It is not possible to assign a high-grade man to watch over each particular circuit, but it must be possible to maintain the stability and the characteristics of the circuit by requiring only the attentions of men who have a great many duties to perform so that repeater stations, including several hundred repeaters, may be manned by only a relatively very small number of men.

**A. P. Allen:** It might be interesting to put a little background on this subject of the modern toll cable. When the line was first built between Chicago and New York in 1892, we couldn't put *any* cable in the line.

At that time we had no load coils, no repeaters, nothing but open wire. We had one thing, however, that made it possible to talk from Chicago to New York, and that was as nearly perfect maintenance as was ever found on a pole line.

Another thing that also came through the lack of toll cable, along in the late nineties, was due to the fact that we didn't know how to get enough open wires between New York and Philadelphia because they didn't have country roads enough for the requisite pole lines. So Mr. McCulloh, who is now president of the New York company, and I worked out a system of operating that gave us sixty paid minutes an hour over each circuit during the busy hour by an exact reversal of the present day A-B toll method. In other words, we had to pass our orders by telegraph wires, and we didn't allow even the toll operator to control, directly, a talking circuit between the two cities. They were all controlled by a switching operator at each end. The instant one circuit was taken down at one end it was put up on another connection. All the preliminaries were arranged on the order circuit before the customer was connected to the circuit, and lost circuit time was practically eliminated.

**E. W. Vanderfleld:** Toll-operating methods are designed to furnish the briefest possible lapse of time between the placement and completion of a message compatible with proper economic costs and the necessities of the subscriber. As a consequence they involve a balance between operating costs and the expense of toll-circuit provision and between the manner of call placement and the resulting service speed.

For the shorter toll hauls of 50 mi. or less where the neighborhood conditions are conducive to relatively large traffic volumes, I believe it will normally be found that operating costs are the predominant factor and that these may be economically conserved through liberality in circuit provision.

Upon this basis if the subscriber is willing to transact his business with any one who may answer at the designated station rather than with a specified person and will furnish the station number, it is practicable and economical to provide a method of no-delay toll operation which is practically identical with local operation throughout its service features.

At ranges extending beyond 50 mi. this toll method has been considered inapplicable chiefly by reason of the supervision limits. At these longer hauls also the circuit costs become ascendant over the operating costs to a degree which makes it expedient to engineer and provide circuits upon a definite delay basis and to thus restrict the two-number operating field.

The increasing informality of toll message placements as signalized by the rise of station-to-station volumes with their significant speed and no-hang-up features, and the generally increasing volumes of toll traffic have together contributed to bring about a marked change in present toll methods. As a consequence it is now planned to extend this station-to-station service where the necessities of the subscriber permit by extending the duties of the recording toll operator to allow her to attempt an immediate completion of all toll calls.

When the subscriber will place his call on a station-to-station basis by giving the station number and where there is an idle toll-line circuit available in less than two minutes, the subscriber will, I understand, secure his connection, regardless of distance, upon the same basis as is now encountered for the short-haul station-to-station service. This will represent the full possibilities of toll service as it is now seen.

If the station number is not known, a particular person is desired, or an idle toll-line circuit is not at once available, the call must necessarily revert to a delay basis similar to that now controlling under present toll-board practise where directory service must be rendered and ticket-distributing time is involved.

It can be reasonably expected that this method will enable between two and three minute service to be given upon a majority of the toll-board-offered calls with no reaction upon the present average speed for the remaining traffic and without directly resulting in increased circuit or operator provision.

# The Vacuum Tube Rectifier

## Oscillographic and Vacuum Tube Voltmeter Study of its Application to B-Voltage Supply for Radio Receivers

BY JOHN H. KUHLMANN[1] and JAMES P. BARTON[2]
Member, A. I. E. E. Enrolled Student

***Synopsis.**—This paper covers investigations made in undertaking the design of a rectifier for use as the B power supply for radio receivers. It determines the most satisfactory type of filter circuit and the appropriate values of inductance and capacitance to give a d-c. output delivered with the least practicable voltage drop and having no fluctuations of sufficient magnitude to interfere with the proper operation of the set. A vacuum-tube peak voltmeter used to detect very small fluctuations is described.*

THE object of this investigation was to determine a good method of design for a vacuum-tube rectifier for converting alternating current into direct current equivalent to that obtained from a battery. The d-c. output should be such that it can be used to properly operate a radio receiving set and loudspeaker without introducing any interference or modulation from the a-c. source. The study of the the eliminator was prompted by the lack of engineering literature[3] on the subject and by the desire of the writers to more fully understand the proper design, the characteristics, and the limitation of the device.

The study is divided into several sections:

1. The rectifier vacuum tubes.
2. Oscillographic study of the action of inductance and capacity (alone and in combinations), upon the rectified wave form.
3. Vacuum tube peak voltmeter study of the small ripple in the load current and its elimination by use of two section filters.
4. Calculation of per cent voltage fluctuation.
5. Conclusions.

The eliminator to be investigated consists of three distinct units,

1. The rectifier proper
2. The filter
3. The load resistance for dividing the load voltage.

The units which make up the general circuits under study are shown in Fig. 1. In Fig. 2 is shown the completed eliminator and its parts as used in this study.

### SECTION 1. THE RECTIFIER VACUUM TUBES

The vacuum tubes used for the rectifier were the obsolete power tubes, UV-202, being the only tubes available at the time. Three tubes were tested; their plate current-voltage and plate current-resistance curves are given in Figs. 3 and 4, respectively.

From the plate voltage-current curves in Fig. 3 it is seen that the tubes $T_1$ and $T_3$ saturate at a much lower current density than $T_2$, which was an unused tube. $T_1$ and $T_3$ had both been used as oscillators; $T_3$ used longer than $T_1$. These curves show that if the rectifier is required to give a peak current of over 100 milliamperes, the rectified current wave will be flat topped.

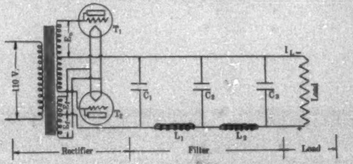

FIG. 1—CIRCUIT DIAGRAM OF EXPERIMENTAL VACUUM TUBE RECTIFIER

Rectifier:
- $E_p$ = 300 volts effective from center-tapped transformers
- $E_f$ = 3.75 volts effective from center-tapped transformer
- $T_1$ = $T_2$ = U V 202 5-watt power tubes with grid connected to plate

Filter:
- $C_1$, $C_2$, $C_3$ are 500-volt condensers. Several values of capacity were used in the experiment
- $L_1$ and $L_2$ are similar iron-cored inductances each having an inductance of about 30 henrys for the normal d-c. excitation. The cores are in two laminated sections, each *L*-shaped; butt joints are used giving small variable air-gaps. Each coil contains about 6200 turns with an average resistance of 645 ohms

Load:
- Low-inductance, wire-wound variable resistance units of ample current capacity. Resistors for final set are wound on flat strips of bakelite and are of fixed value. Several values of resistance were used in the experiments

The plate current-resistance curves, (Fig. 4), were obtained to show the variation of plate resistance with the rectified current. These curves are desirable in order to match tubes and thus obtain equal amplitudes in both halves of the rectified wave.

In the oscillograms, Fig. 2B, $V_1$ and $V_2$ show the current wave forms as per $T_1$ and $T_2$, and $V_3$ gives the resulting current $I_L$, in the resistance load of 8000 ohms. The values of $V_1$, $V_2$, and $V_3$ were taken simultaneously. The circuit diagram is shown in Fig. 2A.

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[1] Assistant Professor of Electrical Design, University of Minnesota.

[2] Minneapolis, Minnesota.

[3] See "Theoretical and Practical Aspects of Low Voltage Rectifier Design When Employing the Three-Electrode Vacuum Tube" by R. D. Duncan, Jr., *Radio Review*, Vol. III, 1922, pp. 59-71 and pp. 114-124. "The Production of Constant High Potential With Moderate Power Capacity" by A. W. Hull, *G. E. Review*, Vol. 19, 1916, pp. 173. "The Thermionic Vacuum Tube" by Van Der Bijl, Chapter VI, McGraw Hill, New York. "Alternating Current Rectification" by L. B. W. Jolley, Chapter X, John Wiley & Sons, New York.

*Presented at Regional Meeting of District No. 5 of the A. I. E. E., Chicago, Ill., Nov. 28-30, 1927.*

The wave forms $V_4$ and $V_5$, Fig. 2B, show the resulting current in the load and the 60-cycle e. m. f. applied to the rectifier, respectively. The oscillograms show that the rectified current is in phase with the applied voltage. This is to be expected, as there is practically no reactance in the load circuit.

The half wave rectifier gives a load current wave form as shown in Fig. 2B by $V_1$ or $V_2$.

The current wave forms, instead of the voltage, were observed throughout this study because the current consumed by the voltage element of the oscillograph is a large portion of the total rectified current and therefore would disturb the circuit and current conditions to be studied.

Fig. 2—Assembled Rectifier with Filter

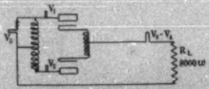

Fig. 2A—Circuit Diagram of Rectifier Without Filter

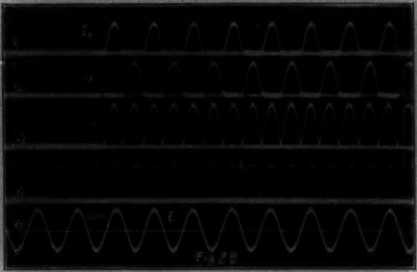

Fig. 2B—Oscillograms for Rectifier Circuit Fig. 2A

$V_1$ and $V_2$ are individual tube output currents. $V_3$ and $V_4$ are load current for full-wave rectifier. $V_5$ is 60-cycle applied voltage

## Section 2. Oscillographic Study of the Action of Inductance and Capacity Alone and in Combination Upon the Rectified Wave Form

*The Effect of Capacity on the Load Current Wave Form.* The addition of capacity across the load resistance of a rectifier, as in Fig. 3A, reduces the ripple in the load current. The operation of the condenser may be explained as follows: When the voltage is applied to the rectifier, the condenser takes a charge and continues

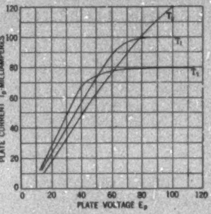

Fig. 3—Plate Current—Voltage Characteristic of Three *U V*-202 Vacuum Tubes

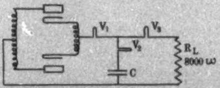

Fig. 3A—Circuit Diagram of Rectifier with Capacity Shunted Across Load Resistance

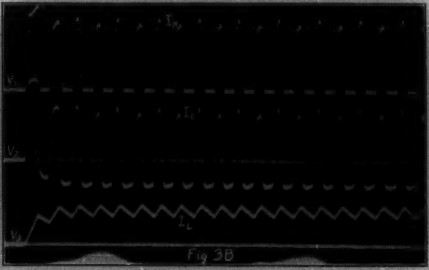

Fig. 3B—Oscillograms for Rectifier Circuit Fig. 3A

$V_1$ is rectifier current. $V_2$ is condenser current. $V_3$ is load current with 2.13 μ f. shunt capacity

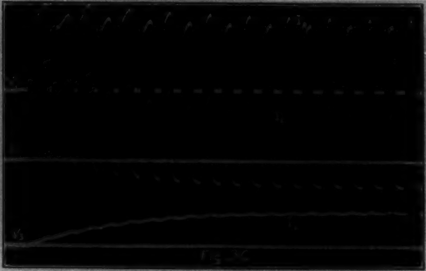

Fig. 3C—Oscillograms for Rectifier Circuit Fig. 3A

$V_1$ is rectifier current. $V_2$ is condenser current. $V_3$ is load current with 12.13 μ f. shunt capacity charging until the rectifier voltage reaches its maximum value. As soon as the rectifier voltage begins to decrease, the condenser begins to discharge and in so doing, builds up a voltage across the tubes which opposes the applied voltage. The rectifier current wave, therefore, takes the shape shown by $V_1$, Fig. 3B, instead of that shown by $V_3$, Fig. 2B. The condenser continues to discharge until the decreasing condenser voltage becomes equal to the increasing rectifier voltage. The load current pulsations are of much smaller amplitude for the circuit shown in Fig. 3A than for the circuit shown in Fig. 2A, because the condenser discharges through the load resistance and supplies the load current during the time the rectifier voltage is passing through zero. The condenser discharges through the load resistance in accordance with the law for the discharge of a condenser through a resistance; that is,

$$i = \frac{E}{R} \epsilon^{-\frac{T}{RC}}$$

From the above discussion, it appears that it should be possible to reduce the load current ripple by increasing the time of discharge of the condenser. For a circuit such as shown in Fig. 3A, the time constant,

$$T = R C$$

Since the load resistance is fixed, the time constant can only be increased by increasing the capacity. Fig. 3B shows the load current when the shunt capacity is 2.13 microfarads and Fig. 3C shows the load current for a shunt capacity of 12.13 microfarads. The oscillograms show that the ripples in the load current are very much less for a shunt capacity of 12.13 microfarads than for a capacity of 2.13 microfarads.

In Fig. 4B, the relation between the condenser current $V_1$, the load current $V_2$, and the impressed 60-cycle e. m. f. $V_3$, is shown. The value of $C_1$ is 2.13 microfarads. The upper waves of $V_1$ show very well the dissimilar characteristics of the rectifier tubes. It is well to point out that in $V_1$ the wave forms above the axis represent the charging current, and below the axis, the discharge current into the load.

Removing either $T_1$ or $T_2$ from the circuit Fig. 3A

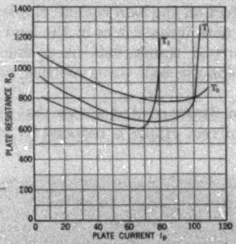

FIG. 4—PLATE CURRENT—RESISTANCE CHARACTERISTIC OF *U V*-202 VACUUM TUBES

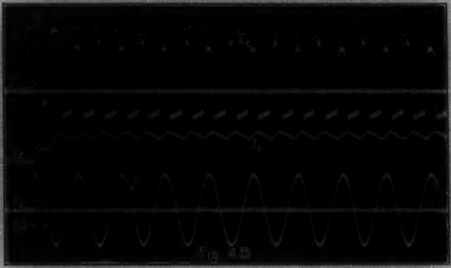

FIG. 4B—OSCILLOGRAMS FOR RECTIFIER CIRCUIT FIG. 3A

$V_1$ is condenser current. $V_2$ is load current with 2.13 $\mu$ f. shunt capacity. $V_3$ is 60-cycle applied voltage

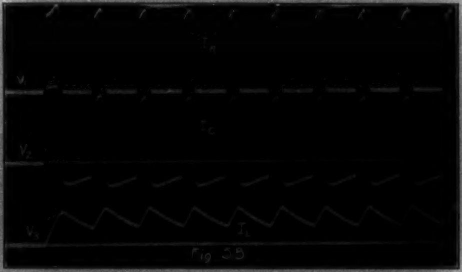

FIG. 5B—OSCILLOGRAMS FOR RECTIFIER CIRCUIT OF FIG. 3A

$V_1$ is rectifier current. $V_2$ is condenser current. $V_3$ is load current with 2.13 $\mu$ f. shunt capacity

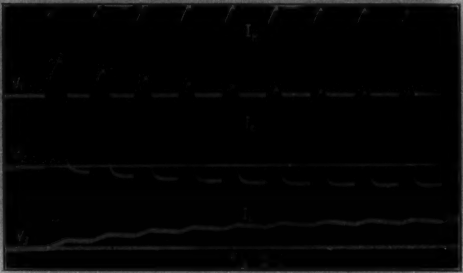

FIG. 5C—OSCILLOGRAMS FOR RECTIFIER CIRCUIT FIG. 3A WITH ONE TUBE

$V_1$ is rectifier current. $V_2$ is condenser current. $V_3$ is load current with 12.13 $\mu$ f. shunt capacity gives a half wave rectifier. The oscillograms in Figs. 5B and 5C show the effect of shunt capacity across the load resistance on the output current of the half wave rectifier. In Fig. 5B, $C_1$ is 2.13 microfarads; in Fig. 5C, $C_1$ is 12.13 microfarads. In both of these oscillograms, $V_1$, $V_2$, and $V_3$ are taken simultaneously, with $V_1$ the rectifier output current, $V_2$ the condenser current, and $V_3$ the resulting load current. In $V_2$ the wave forms above the axis give the charging current, and below the axis, the discharge current to the load.

*Effect of Inductance on the Load Current Wave Form.*

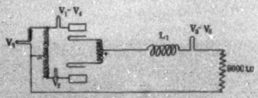

FIG. 6A—CIRCUIT DIAGRAM OF RECTIFIER WITH INDUCTANCE IN SERIES WITH LOAD RESISTANCE

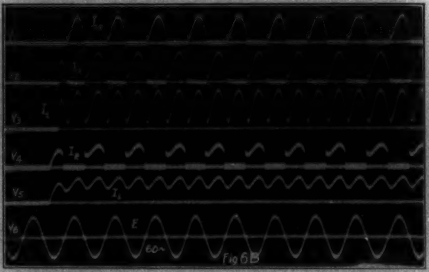

FIG. 6B—OSCILLOGRAMS FOR RECTIFIER CIRCUIT FIG. 6A

$V_1$ and $V_2$ are individual tube output current. $V_3$ is load current with $L_1$ 7.5 henrys. $V_4$ is output current of one tube. $V_5$ is load current with $L_1$ = 30 henrys. $V_6$ is 60-cycle applied voltage

Introducing inductance into the load circuit, as illustrated in Fig. 6A, causes a reduction in the amplitude of the current ripple and also a large drop in the effective load voltage, because of the high $I\,Z$ drop of the inductance. On the other hand, the shunt capacity as shown in Fig. 8A gives a higher effective load voltage than is obtained when both $L$ and $C$ are out of the circuit. This effect of the condenser is obvious from the discussion given above.

In the oscillogram of Fig. 6B, $V_1$, $V_2$, and $V_3$ were taken simultaneously with $L_1$, having an inductance of approximately 7.5 henrys, while $V_1$ and $V_2$ show the individual tube output and $V_3$ the load current. The small hooks on the wave forms of $V_1$ and $V_2$ show that the rectified current lags the impressed e. m. f. because of the series inductance.

The effect of increasing the series inductance to approximately 30 henrys is shown (Fig. 6A) by $V_4$, $V_5$, and $V_6$ in Fig. 6B, $V_4$ being the output of one tube (the output of the other tube being the same), $V_5$ the load current, and $V_6$ the impressed e. m. f. The ripple of $V_5$ is considerably smaller than that of $V_3$, and the hooks on the wave forms of $V_4$ are larger, indicating a greater angle of lag between current and impressed e. m. f. Furthermore, the load current ripple is now practically a sine wave of a frequency twice the input frequency of 60 cycles.

Increasing the inductance still further has only a very small effect on the load current ripple. Half wave rectification, with inductances in the load only, gives a slightly disturbed upper half of a sine wave. The oscillograms for the half wave rectifier are not shown here.

It has been demonstrated above that the amplitude of the load current ripple is reduced by increasing the time constant of the load circuit. For the circuit shown in Fig. 6A, with an inductance of $L_1 = 50$ henrys and a series resistance of 9000 ohms, the time constant is 0.00555 sec. The circuit in Fig. 3A with $C_1 = 12.13$ microfarads and a load resistance of 8000 ohms has a time constant of 0.097 sec. Therefore, the amplitude of the load current ripple should be much less for the circuit with shunt capacity than for the circuit with series inductance. This is clearly shown by the oscillograms, $V_3$ Fig. 3C, for the circuit with shunt capacity and $V_5$ Fig. 6B, for the circuit with series inductance.

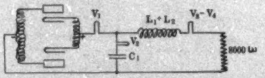

FIG. 8A—CIRCUIT DIAGRAM OF RECTIFIER WITH SERIES INDUCTANCE AND CAPACITY SHUNTED ACROSS RECTIFIER

$C_1 = 12.13\ \mu f.$ $L_1 + L_2 = 60$ henrys

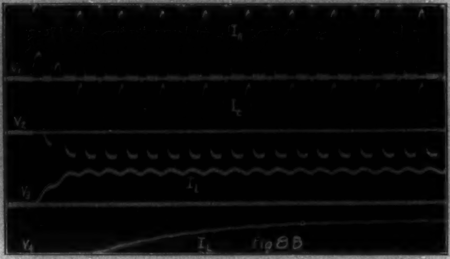

FIG. 8B—OSCILLOGRAMS FOR RECTIFIER CIRCUIT FIG. 8A

$V_1$ is rectifier current. $V_2$ is condenser current. $V_3$ is load current with 2.13 $\mu$ f. shunt capacity. $V_4$ is load current with 12.13 $\mu$ f. shunt capacity

*Effect of Inductance and Capacity on the Load Current Wave Form.* The effect of capacity shunted across the load resistance and the effect of inductance in series with the load resistance on the amplitude of the load current ripple have been shown above. By properly proportioning inductance and capacity, therefore, it should be possible to reduce the amplitude of the load current ripple to a negligible value.

In oscillogram Fig. 8B, for the circuit of Fig. 8A, $V_1$, $V_2$, and $V_3$ were taken simultaneously, $V_1$ showing the current from the rectifier, $V_2$ the condenser current with 2.13 microfarad capacity, and $V_3$ the load current.

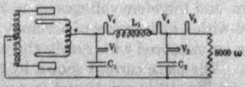

FIG. 9A—CIRCUIT DIAGRAM OF RECTIFIER

Series inductance $L_1$ is 30 henrys. $C_1$ is 4.26 μf. $C_2$ is 4.76 μf.

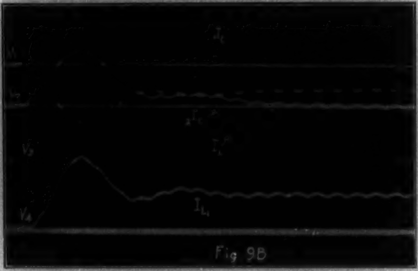

FIG. 9B—OSCILLOGRAMS FOR RECTIFIER CIRCUIT FIG. 9A

$V_1$ is condenser current $C_1$. $V_2$ is condenser current $C_2$. $V_3$ is load current. $V_4$ is current in series inductance

Increasing $C_1$ to 12.13 microfarads gives the load current shown by $V_4$, which is practically a straight line. The per cent ripple in this load current is 1.2 per cent and was determined by the method explained in Section 3 of this paper. With the oscillograph, the current shown by $V_4$ appears as a straight line. It is seen, therefore, that the oscillograph will not show a ripple which is less than about 2 per cent. Since a load current with a ripple of 2 per cent is not satisfactory for "B" battery supply for radio receiving sets, further filtering and other means for detecting the ripple are necessary.

Two more interesting oscillograms are shown to give the action of the second condenser in the filter shown in Fig. 9A. In the oscillogram of Fig. 9B for the circuit shown in Fig. 9A, $V_1$, $V_2$, and $V_3$ were taken simultaneously, with $V_1$ the condenser current of $C_1$, $V_2$ the condenser current of $C_2$, and $V_3$ the load current; $V_4$ is the inductance current and was taken separately, although timed nearly the same.

A starting transient is observed here, and is due to the charging of $C_2$, which had no charge at the start. The transient is observed to be slightly oscillatory but so damped that only two cycles are apparent. The effect is more pronounced in $V_4$. In the steady state, $C_2$ draws a small current, being charged by the 120-cycle current ripple and discharging into the load, thus reducing the load ripple still further. The load current, $V_3$ Fig. 9B, shows a smooth line.

The circuit, Fig. 10A gives an inverted $L$ filter. Oscillograms, Fig. 10B, show $V_1$ the inductance current, $V_2$ the condenser current, and $V_3$ the load current, taken simultaneously, with $C_2$ equal to 2.13 microfarads. The wave forms $V_4$, $V_5$, and $V_6$ show these same currents but with $C_2$ increased to 12.13 microfarads.

Several interesting things are to be observed: First, the highly damped oscillatory transient due to the charging of $C_2$; second, on account of large shunt capacity and a proper series inductance, the ripples in the load current are less pronounced. Increasing the capacity, $C_2$, increases the transient and gives a smooth load current.

## SECTION 3. MEASUREMENT OF THE LOAD CURRENT RIPPLE BY THE VACUUM TUBE PEAK VOLTMETER

The output current of a vacuum tube rectifier was found to be a pulsating current as illustrated in Fig. 2B.

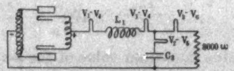

FIG. 10A—CIRCUIT DIAGRAM OF RECTIFIER WITH INVERTED $L$ FILTER

$L_1$ = 30 henrys, $C_2$ = 2.13 or 12.13 μ f.

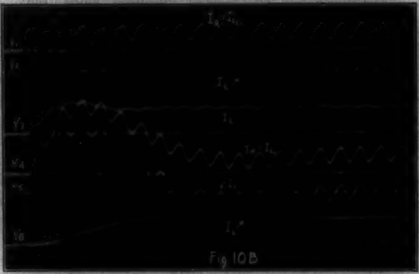

FIG. 10B—OSCILLOGRAMS FOR RECTIFIER CIRCUIT FIG. 10A

$V_1$ is inductance current. $V_2$ is condenser current and $V_3$ is load current when $C_1$ = 2.13 μf. $V_4$ is inductance current, $V_5$ is condenser current and $V_6$ is load current when $C_1$ = 12.13 μf.

It has been shown that the amplitude of the pulsations can be reduced by means of a filter with properly proportioned series inductances and shunt capacities. It was also shown that the oscillograph would not detect a ripple in the load current less than 2 per cent. But a ripple of 2 per cent in the load current of a vacuum tube rectifier is too large for "B" battery supply for radio receiving sets; therefore, the following method for measuring the current ripple was developed.

A current ripple may be looked upon as a periodic alternating current of some wave form superimposed upon a constant direct current. In this case of the output of a vacuum tube rectifier through a filter, the superimposed alternating current is practically a sine wave of 120-cycle frequency. By measuring the two components of the load current, the ripple may be expressed in per cent by

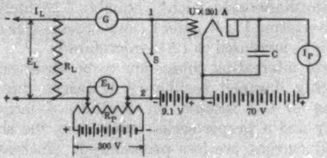

Fig. 11—Circuit Diagram of Vacuum Tube Voltmeter

$G$ = galvanometer. $E_L$ = d-c. voltmeter. $I_p$ = milliameter
$R_L$ = rectifier load resistance

$$\frac{I_{mac}}{I_{dc}} \times 100$$

Here $I_{mac}$ is the maximum value of the a-c. component and $I_{dc}$ is the d-c. component of the rectifier current. After analyzing several methods for measuring these two components of the load current, it was found that the vacuum tube voltmeter would probably be the most satisfactory. The results obtained show that this method is well suited for such measurements.

Fig. 11 shows the circuit diagram of the voltmeter as used for these tests. Here $R_L$ is the load resistance of the rectifier, $E_L$ the load voltage, and $I_L$ the load current, which contains the ripple. A d-c. potentiometer circuit, capable of a voltage variation from 0 to 300 volts, is in series with the grid-filament circuit. The purpose of this potentiometer is: (1) to balance out the effect of the d-c. component and keep it from biasing the grid, (2) to measure the value of the d-c. component of the load voltage indicated by the meter $E_L$. When the switch $S$ is closed, the galvanometer $G$ is used to determine if the potentiometer voltage is equal to the d-c. component of the load voltage. The meter $I_p$ indicates the plate current.

Since the plate current of a vacuum tube is a function of the applied grid voltage, this device can be calibrated and used as a peak voltmeter. The meter was calibrated by passing a known 60-cycle current through a known non-inductive resistance and applying the $I R$ drop to the terminals 1-2 of the meter with the switch $S$ open. Normal grid bias, plate voltage and filament current were used. Since the voltmeter was calibrated on 60 cycles and used on 120 cycles, there is a possibility of a slight error in the readings, due to the fact that the plate current meter $I_p$ will not read the 60-cycle and 120-cycle pulses the same. The error is so slight, however, that it can be neglected.

The calibration curve for this meter is shown in Fig. 12. Two calibration curves are shown, one from zero to 11 volts, and the other from 10.5 to 57 volts. In order that no grid current shall flow, the peak voltage to be measured should not exceed the value of the grid biasing battery voltage, in this case, 9.1 volts. With the grid at a positive potential of 15 volts, the grid current is negligible in comparison with the load current, 0.05 amperes, and therefore voltages up to 25 volts can be measured with a high degree of accuracy and higher voltages can be measured with nearly the same degree of accuracy. The plate current shown by the calibration curves in Fig. 12 is not biased to zero. This is done so that a known zero can be maintained and any deviation noted and corrected. The low-range calibration curve is a close approximation to the plate current-grid voltage static characteristic curve of the UX-201A vacuum tube.

To use the vacuum tube voltmeter, the grid, filament, and plate battery voltages are adjusted to their proper calibrated values. With the complex current in the load resistance, the approximate value of $E_L$ is determined and the potentiometer set to that value. The switch $S$ is closed and $R_p$ varied until the meter $G$ reads zero. Then $S$ is opened and the reading of $I_p$ noted. The corresponding value of the a-c. component of the load voltage is obtained from the calibration curve, Fig. 12. The reading of $E_L$ gives the d-c. component. From these two values, the per cent ripple can be calculated as explained above. In order to obtain satisfactory results, the voltage applied to the rectifier must be constant because very slight changes in the primary voltage will produce large variations in the voltmeter readings across the load. For these tests a constant a-c. voltage was obtained from a synchronous motor-generator set with battery excitation on the generator.

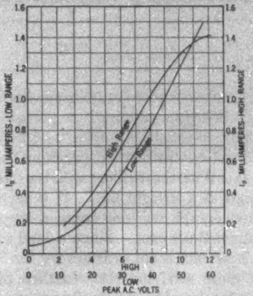

Fig. 12—Calibration Curve for Vacuum Tube Voltmeter

The various filter circuits shown in Fig. 13 were studied with the vacuum tube voltmeter, for which purpose, the full wave rectifier was used with a load resistance of 5100 ohms. With this resistance across the rectifier and no filter, an r. m. s. load current of 0.050 amperes was obtained. The load voltage $E_L$ obtained with the different filter circuits with constant input voltage is shown in the figure. The effect of varying the shunt capacity for each of the filter circuits is also shown in Fig. 13. The results of these tests show that the filters with a small per cent ripple in the load voltage have a high-voltage drop. By combining several of the types of filters shown, one with a small per cent ripple and a low-voltage drop can be obtained.

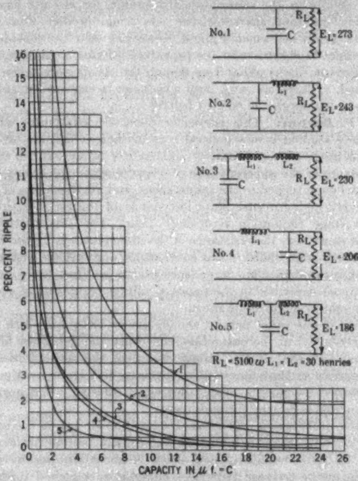

FIG. 13—EFFECT OF VARYING CAPACITY IN VARIOUS TYPES OF FILTER CIRCUITS

One section of a Pi-type filter with the test results is shown in Fig. 14, and a single section of a T-type filter with test results is shown in Fig. 15. The Pi-type filler gives a current with a smaller ripple and also has a lower voltage drop than the T-type filter. The T filter can be improved by adding a capacity $C_2$ across the load as shown in Fig. 16. The results of the test show that the per cent ripple has been reduced to a negligible value, but that the voltage drop in the filter remains unchanged. By adding a third capacity $C_1$, as shown in Fig. 17, the desired results are obtained; that is, the ripple is reduced to a value that cannot be detected by the voltmeter and the voltage drop is the same as for the Pi-filter shown in Fig. 14.

By inserting a pair of high-resistance receivers in the plate circuit of the vacuum tube voltmeter, the ripple can be detected audibly. A ripple that was just audible was found to be equal to 0.08 per cent. To check these results, a small portion of the load voltage was impressed upon the terminals of a 1 to 6 audio-frequency transformer and the secondary connected to the terminals 1-2 of the vacuum tube voltmeter. With a plate current of one milliampere, the hum was just audible. This method of test was used for the circuit shown in Fig. 17. When using the audible method of detecting the ripple, it was found that the removal of the shunt capacity across the load ($C_3$, Fig. 17) introduced a bad circuit noise caused by high frequencies in the load current. It was also noted that a capacity of at least two microfarads should be used, at $C_3$ Fig. 17, to by-pass the high frequencies that tend to enter the load.

The circuit devised for measuring the two components of the load current by means of the vacuum tube voltmeter is believed to be a new application for this type of instrument.

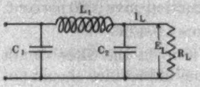

FIG. 14—$E_L$ = 250 VOLTS, $I_L$ = 0.049 MILLIAMPERE

| $C_1$ μ f. | $C_2$ μ f. | Per cent ripple |
|---|---|---|
| 2.13 | 5 | 0.30 |
| 4.26 | 5 | 0.20 |
| 4.26 | 10 | 0.08 |

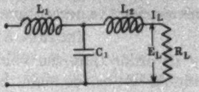

FIG. 15—$E_L$ = 186 VOLTS $I_L$ = 0.037 MILLIAMPERE

| $C_1$ | Per cent ripple |
|---|---|
| 2.13 | 1.62 |
| 4.26 | 0.70 |
| 9.26 | 0.40 |
| 14.26 | 0.27 |

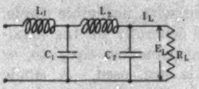

FIG. 16—$E_L$ = 186 VOLTS $I_L$ = 0.037 MILLIAMPERE

| $C_1$ | $C_2$ | Per cent ripple |
|---|---|---|
| 5.0 | 2.38 | 0 + |
| 5.0 | 4.76 | 0 + |
| 10.0 | 4.76 | 0 + |

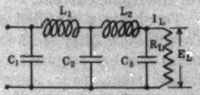

FIG. 17—$E_L$ = 250 VOLTS $I_L$ = 0.049 MILLIAMPERE

| $C_1$ | $C_2$ | $C_3$ | Remarks |
|---|---|---|---|
| 2.13 | 5 | 2 | Slight hum |
| 4.26 | 5 | 2 | Very slight hum |
| 4.26 | 5 | 4 | Not audible |
| 4.26 | 10 | 4 | Not audible |

FIGS. 14, 15, 16, AND 17—FILTER CIRCUITS WHICH WERE TESTED

The amount of ripple and the load voltage for different condenser values are shown herewith. In all cases $L_1$ and $L_2$ equal 30 henrys each and $R_L$ equals 5100 ohms

## SECTION 4. CALCULATIONS OF PER CENT VOLTAGE FLUCTUATION

The percentage voltage fluctuation in the load resistance may be calculated by the formulas given by H. T. Van Der Bijl in his book above mentioned. For the type of filter shown in Fig. 8A, the formula is as follows:

$$\frac{\delta E_L}{E_L} = \frac{2\pi}{\omega C_1 \sqrt{R_L^2 + L^2 \omega^2}}$$

$C_1 = 12.13 \times 10^{-6}$ farads, $L = L_1 + L_2 = 60$ henrys, $R_L = 8000$ ohms, and $\omega = 2\,\pi \times 120 = 754$. The calculations give a percentage voltage fluctuation of 1.49 per cent. The value obtained from the measurments by means of the vacuum tube voltmeter is 1.2 per cent.

For the type of filter shown in Fig. 9A, the following formula applies:

$$\frac{\delta E_L}{E_L} \quad \frac{2\,\pi}{\omega\, C_1\, [R_L^2\, (1 - L_1 C_2\, \omega^2)^2 + L_1^2\, \omega^2]^{1/2}}$$

$C_1 = 4.26 \times 10^{-6}$ farads, $L_1 = 30$ henrys, $C_2 = 5.0$ $10^{-6}$ farads, $R_L = 8000$ ohms, and $\omega = 2\,\pi \times 120 = 754$. The calculations show a percentage voltage fluctuation of 0.289 per cent. The vacuum tube voltmeter method of measuring the percentage fluctuation gave 0.20 per cent.

## Section 5. Conclusions

In order that the voltage drop in the filter circuit should not be too high, the series inductance should not be larger than required to produce a current without ripples. For the filter circuits discussed above, each inductance for the working load current should not be less than 25 henrys. The resistance of each inductance should preferably be kept low,—not greater than 250 ohms. To further reduce the voltage drop, a shunt capacity of not less than four microfarads should precede the inductances to provide a low impedance shunt for the ripple current.

To obtain a rectified current with negligible ripple, two Pi-type filter sections will generally be the maximum number required if shunt capacities equal to, or larger than, four microfarads are used. A single Pi-type filter section can be used to give a ripple of approximately 0.10 per cent if both condensers have a capacity of six microfarads, or larger, and if the series inductance is large, 25 henrys or larger.

## Discussion

**H. S. Read:** Filters have too long been submerged in elegant mathematics. Now we all see what is contributed by the parts of the filter and how filters may be compared. The authors do much to bring theories out of the secrecy of certain laboratores and put them in practical forms.

It is remarkable that a filter can be used for radio. One must greatly reduce the a-c. component in the direct current to make the a-c. inaudible. The reduction is a noteworthy feat because the human ear responds to a tremendous range of exceedingly small engeries. By way of illustration, if one-half inch represents the least sound energy which can be heard, how long a ruler would measure the loudest sound which one can hear without pain? Two-thirds the distance to the sun! Or, if all the talk since colonial days of all the people in the United States were paid for at a common rate for electrical power, you could pay for all the talk with $5.39. We use in everyday life a great range of intensities and very small sound energies. It is amazing that filters can really prevent the hum in radio. The authors show how it is done.

**C. M. Jansky, Jr.:** There are several characteristics of rectifier devices and filters used in receiving sets which are rather interesting, and which apparently are causing some discussion among the manufacturers of such equipment. One of the characteristics of rectifiers is that they usually have fairly high internal resistance with the result that for varying loads the voltage delivered varies widely. That is to say the voltage regulation of the device is extremely poor.

There has been some attempt on the part of manufacturers to adopt standard specifications for rectifiers, and in so doing consideration has been given to the establishment of a standard filter circuit and also a standard load. The specifications for rectifying devices would then be given in terms of the action in this particular circuit.

The conclusion was drawn that if rectifier *A*, in the standard circuit gave such and such results, and rectifier *B* gave such and such results in the same standard circuit, for circuits having entirely different characteristics you could predict what the results would be, which I think, to anyone who has considered the points brought out in the paper by Professor Kuhlmann and Mr. Barton, looks offhand as though too much were taken for granted. Therefore, any light which can be cast on the action of these devices should be very helpful.

**J. P. Barton:** This particular B-battery eliminator which we have studied is of a general type of those which are on the market at the present time.

Because of the apparent lack of proper engineering design and knowledge in regard to the inductances, and, furthermore, of the relatively high internal plate impedance of the rectifier tubes, the voltage regulation is usually poor. For this particular circuit described, the resistance of the inductances is higher than we have recommended in our conclusions, and this coupled with the high internal plate impedance of the rectifier tubes gave, for this set described in the paper, a voltage regulation of about 23 per cent over the useful range.

There is one other point I should like to bring up which has very seriously, in the past years, concerned the B-battery eliminators, and that is the proper design of the series iron-core inductances so that they will maintain a high enough value of inductance to cause a proper degree of filtering when normal load current is flowing through them.

Many inductances on the market have no air gap in the magnetic circuit. Such inductances will usually become saturated when 60 to 100 miliamperes, which is about the normal d-c. flowing in the average B-battery eliminator, is passed through them. Such inductances under these conditions have a very low value of effective a-c. inductance because the working or incremental permeability is low at high inductions corresponding to partial saturation. The ripple consequently would be very high in the load. It is only in a few of the manufacturing companies that the proper design of such inductances is understood. Several men have presented papers in the past several years on the design of such reactors. These papers have made it possible for many to design a reactor at the present time that will carry a d-c. component and yet maintain a high degree of a-c. inductance and keep that inductance over a small variation of the d-c. component which is present in these filter circuits.

**E. W. Vanderfield:** I should like to ask Mr. Barton what is is the effect of the transformer regulation on the transformer supplying the plate voltage to the rectifier. That varies a good deal with the load drawn from the transformer, I believe.

**J. P. Barton:** In the work done here we maintained an input voltage of 300 volts a-c. to the tubes and measured the variation of load voltage due to the effect of different filters. This variation in input voltage was small because the output current variation was over a small range. If such a rectifier were built for varying loads, then it would be quite essential that the plate transformers should have good voltage regulation. However, where a system is built to supply a constant load, then the voltage regulation is not so important unless the primary voltage varies unduly.

The main difficulty in reducing the high voltage regulation of the B-battery eliminator is in the high internal plate impedance of the rectifiers, and the high resistance of the chokes, this latter usually due to economic reasons.

# A Two-Range Vacuum Tube Voltmeter

BY C. M. JANSKY, Jr.[*] and C. B. FELDMAN[†]
Associate, A. I. E. E. Enrolled Student, A. I. E. E.

***Synopsis.**—The design, uses, and limitations of a new circuit employing the three-element vacuum tube as a voltmeter are discussed. Two overlapping ranges of voltage, together with a single operating battery, are the unique features. The effect of wave-form and the elimination of that effect are treated.*

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THE need for a convenient means of measuring small alternating voltages has long been felt in the communication engineering field. The usual type of electromagnetic voltmeter is inadequate for two reasons: (1) Comparatively large current is required to operate it, and (2) its calibration is greatly affected by frequency. Both of these defects are more or less inherent and can probably never be materially reduced. The electrostatic voltmeter, while possessing neither of these defects, has others. Its sensitivity is exceedingly low, requiring the use of an optical system for voltages less than about 25 volts, and its adjustment is very difficult.

The versatile vacuum tube, however, possesses certain characteristics which make it applicable to the measurement of alternating voltages.

Various types of vacuum tube voltmeters are possible. One type uses a variable grid bias voltage which is made to balance out the plate current resulting when an alternating voltage is applied to the grid. This type measures peak voltages. Other types rely upon detector action of the tube. The voltmeter circuit described in this paper uses the grid bias method of detection; this is sometimes also called plate circuit detection.

Fig. 1 shows in schematic form the circuit which will be discussed. In order to obtain a wider range of voltage and still prevent grid current from flowing, two sets of plate and grid bias voltages are provided for. To obtain a means of rigidly fixing both of these voltages, they are taken as resistance drops in the filament circuit. The use of a UX-199 tube, requiring but 60 milliamperes for the filament, makes it possible to supply all power to the circuit from 45-volt, "B" batteries. Best results are obtained when two large-sized, 45-volt units are used in parallel. One set of resistances is used for the low-voltage range, the other for the higher range. When the higher range is in use, the grid is biased beyond the point where plate current normally disappears. For a fixed battery voltage, there exists an optimum proportion of voltages to give both the best, greatest sensitivity and the maximum range.

Since the resistance in the plate circuit is low (of the order of several hundred ohms), the plate current may be considered as vanishing at a bias voltage equal to the plate voltage divided by $\mu$.

Let

$E$ = available battery voltage,

$E_b$ = supplied plate voltage (high range) which equals the voltage between plate and filament for high range,

$e_b$ = supplied plate voltage (low range) which equals the voltage between plate and filament for low range,

$E_c$ = absolute value of grid bias voltage used with high range,

$e_c$ = absolute value of grid bias voltage for low range, optimum value,

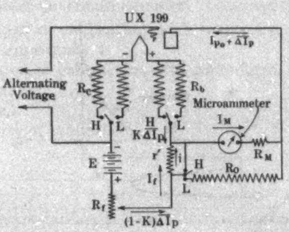

FIG. 1—SCHEMATIC DIAGRAM OF VACUUM TUBE VOLTMETER

$V$ = maximum peak voltage which can be measured on high range without grid current flowing, ($V = E_c$)

$v$ = maximum peak voltage which can be measured on low range without grid current flowing,

$a$ = voltage which when added to $e_c$ would reduce the plate current to zero; see Fig. 2.

Then,

$$e_c = \frac{e_b}{\mu} - a \text{ (} a \text{ is positive)} \tag{1}$$

For the high range,

$$E_c - \frac{E_b}{\mu} \leq v \tag{2}$$

in order to provide continuity between the two ranges. Also, for the high range,

$$E_b = E - E_c \tag{3}$$

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Putting $E_c = V$ into (3) and combining with (2),

$$V - \frac{E - V}{\mu} \leqq v \tag{4}$$

For the low range,

$$e_b = E - b - e_c \tag{5}$$

where $b$ is the auxiliary balancing voltage used in the low range to balance out the normal plate current, $I_{po}$, and which was available in the high range for plate and bias voltage. Putting $e_c = v$ into (5) and combining with (1),

$$v = \frac{E - b - v}{\mu} - a \tag{6}$$

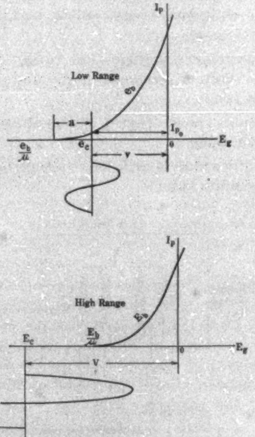

Fig. 2—The Double-Range Design

$e_b$ = plate battery voltage
= plate filament voltage
$e_c$ = operating bias
$\mu$ = voltage amplification factor of tube

Eliminating $v$ between (6) and (4) gives

$$V \leqq (E - b - \mu a) \frac{\mu}{(\mu + 1)^2} + \frac{E - V}{\mu + 1} \tag{7}$$

This equation expresses the maximum peak voltage measurable in a continuous two-range design, in terms of available battery voltage, voltage amplification factor and two design constants, $a$ and $b$.

The constant $a$ is determined by trial and was found to be of the order of one volt for several 199 tubes. Its value is not critical. The constant $b$ is quite arbitrary, if $R_e$ is adjustable for different tubes having different values of $I_{po}$, being equal to $I_{po} R_e$. For $R_e$ = 50,000 ohms, $b$ proved to be about three volts for one tube and five volts for another, using a 45-volt "B" battery as the source of voltage.

Using the guiding equations derived above, the voltages, $E_c$, $E_b$, $e_c$, $e_b$, were selected and the resistances shown in Fig. 1 were obtained on the basis of 60-microampere filament current. Thus, $E_c$ is determined by Equation (7), $E_b$ by (3), $e_c$ and $e_b$ by (4) and (5), respectively. These values are not critical. A filament rheostat of 30 ohms was used so the maximum drop would be greater than 1.5 volts, permitting the use of dry cells to compensate for drop in B-battery voltage. The resistance $r'$ was variable but could be rigidly set for a particular tube. It was found necessary to use a variable 100-ohm rheostat to accommodate the three tubes tested. There is a considerable difference between the normal plate currents for different tubes. In fact, in the tube used in obtaining the data for this paper, a current of nearly two microamperes flows at the high bias, whereas in the other tubes tested, the plate current had entirely vanished at that bias.

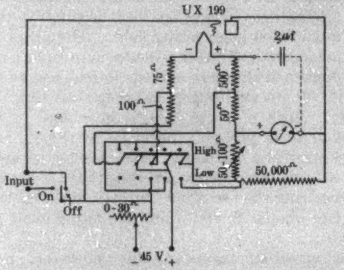

Fig. 3—Wiring Diagram of Assembled Voltmeter

$e_c$ = 4.5 volts
$e_b$ = 33 volts
$E_c$ = 10.5 volts
$E_b$ = 30 volts

Fig. 4—Cabinet, Microammeter, and Condenser

The final arrangement is shown schematically in Fig. 3. A telephone key is used to change from one range to the other. A key is also provided to disconnect the voltmeter from the alternating voltage. This key short-circuits the voltage terminals when the voltage is disconnected, in order to prevent the rise in plate current accompanying the free grid. The entire assembly of tube resistances and keys is mounted in a wooden case as shown in Fig. 4. Terminals are provided for the battery and the microammeter. In the tests herein described, a Rawson-type 501 microammeter having three ranges, 0-20, 0-200, 0-2000 microamperes, was used. An expensive calibrated instrument is not necessary, however; any D'Arsonval galvanometer movement provided with a scale and giving a readable deflection on a few microamperes will prove satisfactory. A more sensitive meter is not desirable due to difficulty which will be experienced in maintaining the false zero. In fact, slight fluctuations in battery voltage as well as shocks applied to the tube are observable on the 0-20-microampere range. The resistances are of the porcelain, tube-wound type and are not especially non-inductive. In the experimental work a condenser was sometimes used across the plate-filament as is shown in dotted lines in Fig. 3. The tube is mounted in a shock-absorbing socket.

Referring to Fig. 1, the application of Kirchoff's Laws to the balancing circuit gives the following equation:

Let

$$I_{po} = I_p \text{ when } I_M = O$$

$$I_f r' = I_{po} R_o \qquad (8)$$

When an alternating voltage is applied to the grid, a mean increase in plate current, $\overline{\Delta I}_p$, occurs. In flowing from the filament, this increase divides between the two filament terminals in the ratio $K$ as shown in the figure.

Thus, when $I_p = I_{po} + \overline{\Delta I}_p$,

$$(I_{po} + [1 - K]\,\overline{\Delta I}_p - i)\,R_o - (I_f + i)\,r' - (K\,\overline{\Delta I}_p + i)\,R_M = 0 \qquad (9)$$

But

$$K\,\overline{\Delta I}_p + i = I_m \qquad (10)$$

Combining (8), (9), and (10),

$$I_M = \overline{\Delta I}_p \frac{R_o + K\,r'}{R_o + R_M + r'} \qquad (11)$$

Equation (11) shows that the calibration is not independent of meter resistance. The lowest range of the Rawson microammeter has a resistance of about 1000 ohms which is not negligible compared with $R_o = 50{,}000$ ohms. The variation between the resistance of meters of various manufacture but of similar range, however, is not sufficient to cause more than 1 per cent error. Equation (11) gives the relative meter current in terms of the actual $\overline{\Delta I}_p$, $K$, and the resistances $R_o$, $r'$, and $R_M$. It is to be recognized that changes in $R_M$ as well as changes in filament rheostat (as made to compensate for falling battery voltage) theoretically change the actual mean increase by virtue of changing the plate circuit resistance. The value of $K$ is also affected. No attempt has been made to obtain a mathematical statement of this; the effect is imperceptible. A further effect of varying the filament rheostat is to cause a slight change in the voltage applied to the circuit through the $\overline{\Delta I}_p \cdot R_f$ drop. This drop for the 30-ohm rheostat is negligible, also, being less than about 0.01 volt.

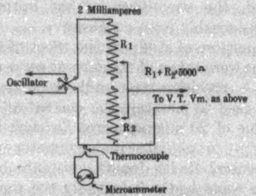

FIG. 5—CALIBRATION CIRCUIT

The following factors determine the usefulness of a tube voltmeter in communication measurements:

1. Variation of calibration with frequency,
2. Input impedance,
3. Variation of calibration with wave-form,
4. Sensitivity,
5. Range,
6. Stability of calibration.

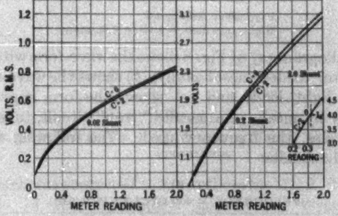

FIG. 6—SAMPLE CALIBRATION VACUUM TUBE VOLTMETER

Low range 1000 cycles
Low range zero = 0 on 0.02 shunt

Information concerning all of these factors has been obtained in the laboratory.

Fig. 5 shows the circuit used to calibrate the tube voltmeter. This circuit was also used for much of the test work. Calibration curves for the model studied in the laboratory are shown in Figs. 6 and 7. In addition to the fact that grid current reduces the input impedance, it biases the grid differently when flowing through different resistances. Tests made using no grid bias verified this. The flow of grid current thus limits the range.

In order to interpret some of the subsequent results more intelligently, the effect of wave-form will be treated now. A consideration of the manner in which the mean increase in plate current arises shows that, in general, wave-shape does affect calibration. For almost all of the test work, the source of alternating current was a Western Electric 8-A oscillator comprising an oscillator, voltage amplifier, and power amplifier. Under load, the wave-form of the output current departs considerably from a sine-wave.

For the purpose of studying the effect of wave-form, oscillograms were taken of the current wave at different loadings. A precision-type radio-frequency milliammeter was used to maintain the current at a constant r. m. s. value of 20 microamperes for each load. The voltage drop to actuate the voltmeter was taken across a General Radio decade resistance box so that the voltage wave had substantially the same form as the current wave.

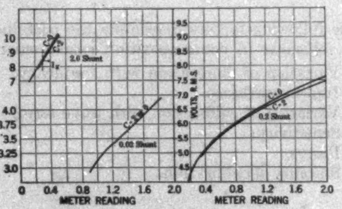

FIG. 7—SAMPLE CALIBRATION VACUUM TUBE VOLTMETER

High range 1000 cycles
High range zero = 0.14 on 0.02 shunt

Oscillogram (*a*) of Fig. 8 shows the wave-form with the oscillator loaded most heavily; (*b*) shows the wave-form under light load; and (*c*) shows the form improved slightly by means of a parallel "trap" circuit, tuned to 400 cycles, the frequency used. The following table gives the results:

TABLE I
FREQUENCY = 400 CYCLES PER SEC.

| Volts r. m. s. | Reading | Zero scale | Reading | Scale | Cond. m. f. | Wave-form | Volts from curve | Per cent error |
|---|---|---|---|---|---|---|---|---|
| 7.00 | 0.18 | 0.02 | 1.755 | 0.2 | 0 | *a* | 7.36 | +4.90 |
| *7.00 | 0.18 | 0.02 | 1.252 | 0.2 | 0 | *a* | 6.73 | * −4.01 |
| 7.00 | 0.18 | 0.02 | 1.433 | 0.2 | 0 | *b* | 6.97 | −0.42 |
| *7.00 | 0.18 | 0.02 | 1.388 | 0.2 | 0 | *b* | 6.90 | * −1.45 |
| 7.00 | 0.18 | 0.02 | 1.460 | 0.2 | 0 | *c* | 7.00 | 0 |
| *7.00 | 0.18 | 0.02 | 1.403 | 0.2 | 0 | *c* | 6.93 | * −1.01 |
| 7.00 | 0.18 | 0.02 | 1.890 | 0.2 | 2 | *a* | 7.40 | +5.40 |
| 7.00 | 0.18 | 0.02 | .. | 0.2 | 2 | *b* | .. | .. |
| 7.00 | 0.18 | 0.02 | 1.518 | 0.2 | 2 | *c* | 6.96 | −0.57 |
| 0.70 | 0 | 0.02 | 1.345 | 0.02 | 0 | *a* | 0.701 | +0.14 |
| 0.70 | 0 | 0.02 | 1.340 | 0.02 | 0 | *b* | 0.700 | 0 |
| 0.70 | 0 | 0.02 | 1.340 | 0.02 | 0 | *c* | 0.700 | 0 |

*Oscillator terminals reversed.

The per cent error in the above readings was referred to the reading with wave-form (*c*), designated by zero error for the reason that it coincided with the calibration. It can be seen that while none of the wave-forms photographed is so distorted as to be considered unsuitable for most work, errors in measurement may result if tube voltmeters are used, unless precautions are taken to eliminate them.

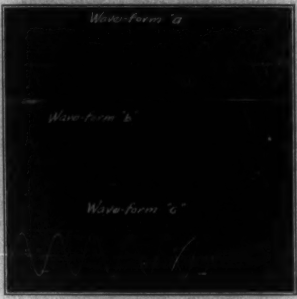

FIG. 8

The curves given in Fig. 9 show that the calibration does not vary appreciably with frequency. For each set of curves, a constant voltage across a non-inductive resistance was obtained by the aid of a precision thermal milliammeter. As would be expected, the use of a condenser connected between plate and filament prevents the slight falling off of the curves for higher frequencies due to the inductance in the plate circuit.

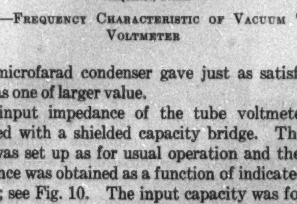

FIG. 9—FREQUENCY CHARACTERISTIC OF VACUUM TUBE VOLTMETER

A two-microfarad condenser gave just as satisfactory results as one of larger value.

The input impedance of the tube voltmeter was measured with a shielded capacity bridge. The voltmeter was set up as for usual operation and the input impedance was obtained as a function of indicated plate current; see Fig. 10. The input capacity was found to be approximately 30 $\mu \mu$ f. and the input conductance was found to be of the order of 0.004 micromhos. The conductance increases rapidly as the grid approaches a positive potential. At 1000 cycles, the impedance is about five megohms.

The above measurements show that the input impedance of the vacuum tube voltmeter is entirely satisfactory for use in most communication engineering measurements. The device cannot be used to measure voltage across a condenser unless a conductive path exists between condenser plates, inasmuch as the voltmeter has no grid leak of its own.

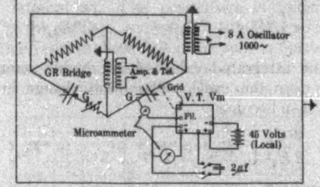

Fig. 10—Schematic Diagram of Impedance Bridge

Further notes on the method of calibration may be of interest. A frequency of 1000 cycles per sec. was used in the circuit shown in Fig. 5. The current was kept constant at two milliamperes and the load was kept fixed at 5000 ohms, non-inductive. The thermocouple, which was of the heater coil type, was calibrated with two milliamperes direct current immediately before use. The wave-form from the oscillator was satisfactory as the oscillator was not overloaded. Reversal of oscillator terminals had but little effect. Calibration curves were obtained both with and without two microfarads between the plate and filament. Condenser curves should be used for all frequencies about 100 cycles; below 100, the no-condenser curves should be used.

A re-calibration of the voltmeter described, made after about 40 hours of service, was found to coincide with the original calibration to within the limits of accuracy of the standardizing voltage. This is to be expected, as the method of adjusting for the false zero compensates for any change in emission. The change in filament current necessary to so compensate makes insignificant change in the operating voltages. As the tube nears the end of its life, however, its characteristics will change and compensation for the change in emission will not suffice, in general, to retain the calibration.

Aside from the use of the vacuum-tube voltmeter as a calibrated instrument to measure voltages, there is a wide field of use in which the device may be used as an intermediary in measuring a ratio of voltages. An illustration is the comparison of two impedances. In Fig. 11 is shown the scheme for comparing a scalar impedance with a resistance. The voltmeter is first connected across $Z_x$ and the deflection noted, or the oscillator output is adjusted to give a conveniently readable deflection; it is then transferred to the voltage divider which is adjusted to give the same deflection. Care must be taken, if the wave-form is unsymmetrical with respect to the axis, to impress the same side of the wave toward the grid. In comparing an impedance of high phase-angle with a resistance, error arises even then if the wave-form is bad; for the harmonics in the current wave contribute to the voltage in different degrees in the reactance and resistance. This is exemplified by the fact that the measured impedance is different for reversed oscillator terminals, using the correct voltmeter connections as shown in Fig. 11. Measurements comparing the impedance of a 100-millihenry inductance with that of a resistance showed a discrepancy of the order of 5 per cent upon reversing oscillator terminals. When an inductance was connected in series with the resistance and the impedance of the resistance reduced to the same value as that of the inductance, thus making the phase angles in the two impedances equal, this discrepancy disappeared. Excellent sensitivity was obtained. The error of measurement was less than 0.5 per cent.

The tube voltmeter circuit under discussion cannot be used, without modification, except where the arithmetic mean of the voltage measured is zero. Measurements are frequently desired, however, of inductance or alternating voltage in iron core coils, transformers, etc., while carrying a polarizing or magnetizing current. One method of making such measurements is to employ the grid stopping condenser type of voltmeter. As pointed out by W. B. Medlam and U. A. Oschwald,* this type of voltmeter, however, has inherent objections such as enormous wave-form error, restricted range, and some frequency error. A preferable means of making the above measurements for transformers is to employ the plate detection voltmeter in a circuit shown in Fig. 12 which was suggested to the authors by Mr. J. P. Barton, late of this laboratory, now of the Westinghouse Electric & Mfg. Co. By making $r$ sufficiently low, of the order of a few hundred ohms, the current taken by the transformer can be reduced to a negligible amount; or, if not, corrections can be readily applied. Very satisfactory results have been obtained with this circuit in measuring voltage ratios of transformers, the manipulation being similar to the comparison of impedances. Here, the wave-form error cannot well be eliminated by a choice of voltmeter connections, and the best solution is to employ a good wave-form which, of course, is desirable from all standpoints.

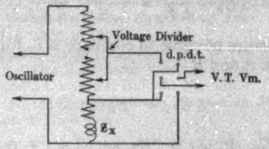

Fig. 11—Comparison of Impedances Using Vacuum Tube Voltmeter

## Elimination of Wave-Form Error

Writing $I_p$ as a function of $E_g$ alone, as can be done when the plate circuit impedance is very low and $E_p$ remains substantially constant,

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*Bibliography, 1.

$$I_p = f\,(E_g)$$

Let the steady current and voltage be $I_{po}$ and $E_{go}$, respectively, and express the superposition of a variation in $E_g$ as

$$I_{po} + \Delta\, I_p = f\,(E_{go} + \Delta\, E_g)$$

Expanding this by Taylor's theorem,

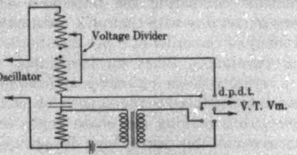

FIG. 12—CIRCUIT FOR MEASURING TRANSFORMER CHARACTERISTICS

$$\Delta\, I_p = \Delta\, E_g \cdot \frac{d\; I_p}{d\; E_g} + \frac{\Delta\, E_g^2}{2} \cdot \frac{d^2\, I_p}{d E_g^2} + \frac{\Delta\, E_g^3}{6} \cdot \frac{d^3\, I_p}{d\, E_g^3} + \ldots$$

In general, this series would not greatly facilitate the study of the effect of wave-form where the variations $E_g$ and $I_p$ are wide, inasmuch as then the derivatives would vary over the range. In particular, however, if $I_p = A\,(K + E_g)^2$, the second derivative is constant $(= 2\, A)$ and all higher order derivatives vanish. Under this condition,

$$\Delta\, I_p = \Delta\, E_g \cdot \frac{d\; I_p}{d\; E_g} + \frac{\Delta\, E_g^2}{2}\, \frac{d^2\, I_p}{d E_g^2} \;\ldots \tag{1}$$

It now becomes possible to compare $\Delta\, I_p$ for two unlike wave-forms $A$ and $B$,

Let

$$\Delta\, E_{g_A} = {}^{M}E_A \sin\, \omega\, t \quad \ldots \tag{2}$$

and let

$$\Delta\, E_{g_B} = {}^{M}E_{B_1} \sin\, \omega\, t + {}^{M}E_{B_2} \sin\,(2\; \omega\, t + \alpha_2) + {}^{M}E_{B_3} \sin\,(3\; \omega\, t + \alpha_3) + \ldots + {}^{M}E_{B_n} \sin\,(n\; \omega\, t + \alpha_n) \tag{3}$$

Further, let

$${}^{M}E_A = \sqrt{{}^{M}E_{B_1} + {}^{M}E_{B_2} + \;.\;.\;.\; + {}^{M}E_{B_n}} \tag{4}$$

to express equal r. m. s. values. Substituting (2) in (1) and integrating over a fundamental cycle to obtain the average change in plate current, $\Delta\, I_p$,

$$\overline{\Delta\, I_{p_A}} = \frac{1}{2} \cdot \frac{d^2\, I_p}{d\, E_g^2} \cdot \frac{1}{2\pi} \int_0^{2\,\pi} [{}^{M}E_A \sin\, \omega\, t]^2\, d\,(\omega\, t)$$

as the periodicity of the first term causes it to vanish. Performing the integration,

$$\overline{\Delta\, I_{p_A}} = \frac{d^2\, I_p}{d\, E_g^2} \left[ \frac{{}^{M}E_A^2}{4} \right] \tag{5}$$

Now, substituting (3) in (1), gives for the mean change,

$$\overline{\Delta\, I_{p_B}} = \frac{d^2\, I_p}{d\; E_g} \cdot \frac{1}{4\;\pi} \int_0^{2\pi} \Bigg[ \sum_{K=1}^{n} {}^{M}E_{B_K}^2 \sin^2\,(K\; \omega\, t + \; \alpha_K) + \sum_{\substack{r=1\\ r\neq s}}^{n} \sum_{s=1}^{n} {}^{M}E_{B_r}\, {}^{M}E_{B_s} \sin\,(r\; \omega\, t + \alpha_r) \sin\,(s\; \omega\, t + \alpha_s) \Bigg]\, d\,(\omega\, t)$$

The integrated value of the first summation can be shown to be

$$\pi \left[ {}^{M}E_{B_1}^2 + {}^{M}E_{B_2}^2 + \;.\;.\;.\; + {}^{M}E_{B_n}^2 \right]$$

while the integrated value of the double summation is zero over the cycle. The mean change in plate current then becomes

$$\overline{\Delta\, I_{p_B}} = \frac{d^2\, I_p}{d\, E_g^2} \left[ {}^{M}E_{B_1}^2 + {}^{M}E_{B_2}^2 + \;.\;.\;.\; + {}^{M}E_{B_n}^2 \right]$$

By (4) we have

$$\overline{\Delta\, I_{p_B}} = \overline{\Delta\, I_{p_A}}$$

which shows that for the quadratic characteristic the wave-form error vanishes. In special cases, the discrepancy between two unlike wave-forms may vanish for a non-quadratic function, but this will not be so in general, as a consideration of the graphical treatment clearly shows.

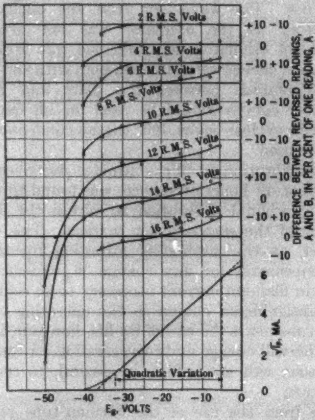

FIG. 13—VARIATION OF WAVE-FORM ERROR WITH BIAS

The significant thing about the above demonstration is that the vacuum tube voltmeter may be freed from its greatest limitation by confining the range of variation of grid voltage to a substantially quadratic portion of the curve. No previous treatment of this fact by others has been found by the authors.

Certain types of tubes display characteristics well suited for use in eliminating wave-form error. The low-$\mu$ power tubes, in general, have a relatively wide range of grid voltage over which the characteristic is quadratic. Fig. 13 shows the plot of the square root of plate current as a function of $E_g$ for a UX-171 tube, and shows a range of about 27 volts over which the straight line indicates a constant second derivative. That the wave-form error is negligible over this region is shown by the other experimental curves of Fig. 13. They show the percentage difference between reversed readings for the unsymmetrical wave-form (*a*), previously referred to. The percentage is taken with respect to the readings reversed the same way throughout. These curves show that if the tube is operated at a bias voltage near the center of the quadratic region, a voltage considerably in excess of the quadratic limitation may be applied without wave-form error. Thus the 16-volt r. m. s. curve shows no error when operated at -20 volts bias although the peak of the wave is approximately 23 volts and exceeds the limit of quadratic variation by eight volts.

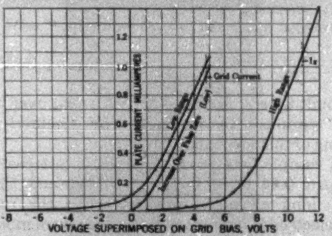

Fig. 14—Static Characteristics of Vacuum Tube Voltmeter

Fig. 14 shows the $I_p - E_g$ curves for the voltmeter described herein. The wave-form error throughout the low-range was found to be negligible for any of the wave-forms studied, despite the fact that the departure from quadratic variation is quite marked. It is only when the normal bias voltage is considerably in excess of that for which the plate current vanishes, that *slight* differences in wave-form are manifested by different readings in plate current. The plate current then depends solely on that portion of the voltage wave which projects beyond the vanishing point, and any hump or tip on the wave which might be insignificant compared to the entire wave is strongly instrumental in affecting the plate current.

Too much emphasis should not be placed on the elimination of wave-form error. The mere fact that a voltmeter reads r. m. s. volts independently of wave-form does not, of course, permit the indiscriminate use of any wave-form. In fact, in some instances, it might be desirable to use a voltmeter which would, by reversing terminals, detect an unsymmetrical wave-form.

Although the two-range voltmeter described herein is not capable of wave-form error elimination, its usefulness is not necessarily impaired. It does, however, on the higher range tend to *exaggerate* differences in wave-form. In passing, it may be said that this exaggeration is greater, according to the authors' beliefs, in the grid stopping condenser type of voltmeter than in the plate detection type. In fact, the former partakes largely of the characteristics of a *peak* voltmeter.

Of the six features of the vacuum tube voltmeter which were set down at the outset, the following may be said in summary concerning the two-range type studied by the authors:

1. Frequency has but little effect on the operation and this effect can be eliminated by the use of the by-passing condenser,

2. The input impedance is high, of the order of several megohms, and the power factor is low,

3. Differences in wave-form are exaggerated but not, for commercial wave-forms, objectionably so,

4. The senstivity is higher, perhaps, than that of most other communication-frequency measuring instruments. On the instrument designed by the authors, changes of 0.01 volt on the low end of the range, and changes of 0.05 volt on the high end are readily detectable,

5. The range is inherently low, covering, probably, a band of voltages from a tenth or a few tenths of a volt to about 10 volts,

6. The stability of calibration over the entire life of the tube is questionable. Experiment showed, however, that in general the calibration could be expected to remain constant for periods of operation of over 40 hr.

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6. Hoare, S. C., *A New Thermionic Instrument*, Jour. of the A. I. E. E., Sept. 1927, p. 958

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## Discussion

**J. P. Barton:** The vacuum-tube voltmeter as applied to the communication industry today, as Mr. Jansky has pointed out, is certainly an outstanding means of measurement on circuits where no current is to be absorbed by the measuring instrument.

The vacuum-tube voltmeter is very versatile in creating a means of measuring constants of circuits which was not possible several years ago by the older means common to power work in the measuring of currents and voltages.

One of the big advantages, as has been pointed out, is in the wave-form errors which do exist and which can be eliminated by using the quadratic portion of the static characteristic curve of the tube. From personal experience in the use of vacuum-tube voltmeters in measuring and comparing inductances against standards of inductance, it is very necessary to watch out for the effect of a bad wave form. To keep the wave-form error to a minimum or zero, it is best to make the impedance and phase angles equal for both the known and unknown inductances, and to present the same potential side of each impedance to the grid of the vacuum-tube meter. By this means very accurate comparisons are possible and it offers a quick means of calibration of the inductance.

# The Influence of Residual Air and Moisture
## In Impregnated Paper Insulation

BY J. B. WHITEHEAD[1] and F. HAMBURGER, JR.[2]
Fellow, A. I. E. E. Associate, A. I. E. E.

***Synopsis.**—The paper describes experiments in study of the separate influence of residual air and moisture in impregnated paper as used for the insulation of high voltage cables.*

*Some sixty similar samples are prepared, dried, evacuated, and impregnated under the same program, except as regards the pressure of evacuation and impregnation. In groups of three, the samples were evacuated at various absolute pressures between 2 mm. and 76 cm. Hg.*

*The samples were brass tubes 2.54 cm. in diameter, 122 cm. long with 25 layers of wood pulp paper applied in the usual lapping spirals. Each sample was equipped with outside test and guard electrodes.*

*Throughout their entire history, i. e., before and after impregnation, observations were made on the samples of their dielectric absorption and their final conductivity. These studies have led to the conclusions as to the influence of moisture.*

*After impregnation, the samples are studied as to power-factor and dielectric loss over the range of electric stress 20 to 300 volts per mil, and of temperature 20 deg. cent. to 80 deg. cent. These studies have led, principally, to the conclusions of the influence of residual air. They show clearly the importance of thorough impregnation, and the conditions under which it may be accomplished. The causes of rising power-factor—voltage curves and methods of avoidance are clearly indicated.*

*The principal results and conclusions are given at the end of the paper.*

THE sharp rise in the power-factor—voltage curve of impregnated paper insulation, such as found in high-voltage cables, is commonly attributed to the ionization of entrapped air or gases. The present investigation was undertaken with a view to studying the influence of different amounts of entrapped air in such insulation. The general plan adopted was to construct a large number of samples as nearly identical as possible, to impregnate them under similar conditions, except as regards the air pressure, and to follow the electrical behavior of the samples as closely as possible throughout their entire history. In addition to the results of the study of the influence of entrained air, other interesting data on impregnated paper insulation have also been obtained.

### The Test Samples

Each test sample consisted of a brass tube 2.54 cm. (1 in.) in diameter and 121.9 cm. (4 ft.) long. Each tube was cleaned and polished and then received its wrapping of cable paper. The wood pulp paper furnished by a prominent manufacturer, was 0.01016 cm. (0.004 in.) thick, and 2.54 cm. (1 in.) wide. The tube was put in a lathe and a leather friction grip mounted on the carriage of the lathe fed the paper on to the tube spirally in the usual manner. In each layer the successive turns lapped slightly, the lap varying from 0.08 cm. (1/32 in.) down to a close butt contact. The laps or joints in successive layers were displaced successively by approximately 0.635 cm. (¼ in.). The tension on the paper during wrapping was between 3.5 and 5 lb. The greater number of samples were wrapped with 25 layers of paper, a few having 40 layers. At each end of the paper wrapping additional layers built up the thickness to twice that over the body of the sample. These ends were secured with a wrapping of linen thread.

Each sample was provided with a test electrode of sheet lead 0.04 cm. (1/64 in.) thick, and 71.12 cm. (28 in.) long placed equidistant from the two ends. Guard electrodes 5.08 cm. (2 in.) wide were mounted on either end of the test electrodes. The electrodes were cut from sheet lead, carefully smoothed out and wrapped on in single pieces with a longitudinal opening of about 0.08 cm. (1/32 in.) at the butt joint. The electrodes were firmly held in place and in close contact with the paper by a continuous band of linen thread wound over the outside. Fig. 1 shows a finished view of the samples before impregnation.

FIG. 1—SPECIMENS IN DRYING BOX

There were 60 test samples in all, divided into 20 groups of three each. The three samples in each group received the same treatment throughout. The treatment of the several groups differed only as regards the air pressure at which impregnation took place.

### The Drying Chamber

The drying chamber consisted of a wooden box 182.9 cm. (6 ft.) long, 60.9 cm. (2 ft.) wide, and 45.72 cm. (18 in.) deep, with hinged top and front. The box was lined throughout with sheet asbestos. The bottom of the box was completely covered

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*Presented before the Baltimore Section of the A. I. E. E. December 16, 1926.*

with a grid of bare resistance wire mounted zigzag on small porcelain insulators. Subdivision of this wire into several circuits provided an electric heater readily adjustable for any desired temperature. A view of the interior of the drying chamber is seen in Fig. 1. The specimens, three in a group, were supported on porcelain insulators several inches above the heater wire. A slow draft of air was drawn through the box continuously by means of a small rotary fan and holes in the two ends of the box. The equipment also included three resistance thermometers, which fitted snugly into the interiors of the brass tubes forming the central conductors of the samples, reaching to about their central portions. A thermostat with relay connection operating on the heater circuits permitted maintaining the box at uniform temperature over long periods of time. Bakelite micarta bushings in the top of the box permitted introduction of 1500 volts, direct current, to the central conductor of each sample and connections to the test electrodes, thus permitting study of the volt-ampere characteristics of the insulation throughout the period of drying.

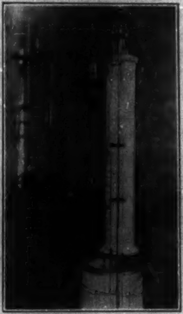

Fig. 2—Evacuating and Impregnating Equipment

### IMPREGNATING CHAMBER

The impregnating chamber consisted of a steel tube of 12.7 cm. (5 in.) inside diameter, 213.4 cm. (7 ft.) long, 0.32 cm. (0.125 in.) wall thickness. The tube was placed in vertical position (see Fig. 2) and the test samples lowered into it by means of a special rack. Both top and bottom of the tube were equipped with special steel flanges. That at the bottom was slotted so as to completely close the end of the tube, except for a 0.635-cm. (¼-in.) pipe opening in the center. The flange at the top had a carefully machined surface on which could be sealed an outside plate providing the necessary air tight joint. The top and bottom flanges and all pipe connections were carefully brazed to the tube. Over the lower 152.4 cm. (5 ft.) of the tube there were wound two circuits of resistance wire mounted on wooden strips, providing means for heating the impregnating chamber. A galvanized iron casing was built around this lower portion of the tube. The jacket so made was filled with transformer oil, completely covering the heating coils. The outside surface of this oil jacket was enclosed in pipe covering and asbestos cement as heat insulation. The upper portion—about 60.96 cm. (2 ft.) of the steel tube—was wrapped with ten turns of 0.318 cm. (1/8-in.) copper tubing through which water was passed continuously. The purpose of this feature was to maintain the top flange at relatively low temperature in order that a wax seal might be used for closing the impregnating chamber. This afforded a convenient and rapid method for handling the necessarily frequent opening and resealing of the impregnating chamber. The evacuating system consisted of a motor driven oil immersed vacuum pump, connected with the impregnating chamber through a system of glass tubing which included calcium chloride or other type of drying chamber, a vacuum gage, a trap for receiving any compound which might go over into the vacuum system, and the usual stop-cocks which also provided for the admission of dry air. The vacuum gage was of the usual manometer type, permitting a minimum reading of one mm. Hg., which was the lowest pressure used. The connection to the vacuum system was near the top of the impregnating chamber.

Immediately below the bottom of the impregnating tube there was placed a 10-gal. tank in which the compound was heated preparatory to impregnation. This tank was surrounded by an outer oil jacket which contained electric heating circuits, the whole being covered outside with heat-insulating material. The pipe connection to the bottom of the impregnating chamber extended to the bottom of the compound tank and was equipped at its lower end with a special high grade valve operated from above the level of the compound.

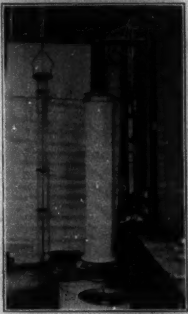

Fig. 3—Impregnating Rack and Tank

For impregnation, the specimens were mounted on a special rack built around a 1.27-cm. (½-in.) square brass rod (see Fig. 3). This rod carried three wooden supports into which the three specimens fitted in triangular arrangement. Near the top of the rod there was mounted a bakelite terminal block through which there passed 9 small glass tubes. These tubes extended down through the wooden supports and carried test leads to the electrodes and to three resistance thermometers which were inserted in the central tubes of the three specimens. The central conductor or tube of each specimen was connected to the main brass rod of the rack which constituted the high-voltage terminal for absorption and conductivity measurements. Each of the glass tubes terminated just above the bakelite terminal block and was fitted with a small brass cup connected to the lead passing through the tube. The cups were filled with mercury, receiving platinum wires which, in their turn, were sealed into glass tubes mounted in the brass plate which finally closed the top of the impregnating tube. This plate was about 17.78 cm. (7 in.) in diameter and 1.27 cm. (½ in.) thick. The rack carrying the specimens was suspended under the center of this brass plate by three brass studs passing through the bakelite terminal block. The three samples could thus be mounted in the rack, the 10 necessary electrical connections promptly made, and the whole lowered into the impregnating chamber. The brass plate rested on the top flange of the impregnating chamber to which it could be rapidly sealed with ordinary laboratory wax. By this arrangement electrical measurements were possible during the period of impregnation and cooling. An additional oil encased heating bath was provided so that the 4-gal. can, in which the compound was received from the manufacturer, could be heated before opening. The compound was never exposed to the air except at high temperature, and then only for the period necessary to adjust to final temperature in the impregnating reservoir.

FIG. 4—HIGH-VOLTAGE TEST BOX

## HIGH-VOLTAGE TEST BOX

The high-voltage test chamber consisted of a wooden box approximately 182.88 cm. (6 ft.) long and 60.96 cm. (2 ft.) wide and 35.56 cm. (14 in.) deep, with hinged front and top (see Fig. 4). The box was lined throughout with sheet asbestos. It contained two galvanized iron troughs, one inside the other, the space between being filled with transformer oil heated by submerged electric circuits. The specimens were mounted on porcelain supports placed on the bottom of the inner trough, which was then filled with the compound in which the specimens had been impregnated. Occasional measurements were taken with no compound in this tank. Lying longitudinally in the bottom of the tank and between the specimens were three resistance thermometers placed so that they would read the temperature of the compound in close proximity to the center of each specimen. Pipe connections in the bottoms of the tanks permitted ready removal of the compound and the oil of the heating bath.

The high-voltage connections were made through bushings made of micarta tubes filled with impregnating compound. These were mounted in the top of the box at one end, connection being made to the central tubes of the specimens by tight fitting plugs. Connections to the test electrodes were also brought out through micarta bushings near the center of the top of the box. Baffle plates and ground shields were so located in the inner trough that the test electrodes of the specimens were completely screened, not only from electrostatic high-voltage influence, but also from any possible leakage due to conductivity in the compound forming the bath. These plates and screens, together with the troughs holding the specimens, were connected electrically to the guard electrodes and all were insulated from ground, the final connection to ground being made through adjustable resistances to be described in a later paragraph.

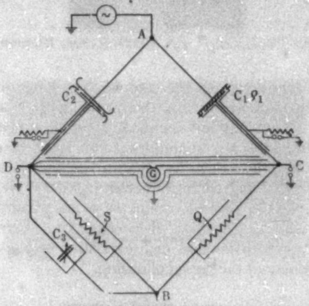

FIG. 5—SCHERING BRIDGE WITH ELECTROSTATIC SCREENING

## HIGH-VOLTAGE MEASURING EQUIPMENT

The source of alternating voltage was a 5-kw., single-phase, 125-volt, 60-cycle, motor-driven generator having a smooth wave. The motor-generator set was driven from a large storage battery and provision was made for close frequency and voltage control from the observer's position. The voltage was stepped up by means of a 10-kv-a. transformer of ratio 115 to 34500 volts. The accurate determination of voltage on the high-voltage side was made with a two circuit screened potential divider permanently connected across the high-voltage side of the transformer. Each circuit of this potential divider had a resistance of 1.6 megohms and it thus constituted a moderate steadying load on the generator. The voltage was computed from the current as measured in the ground side of one of the resistance circuits.

The method of measurement of power factor was a modified form of Schering bridge. A schematic diagram of connections is shown in Fig. 5. As is well known this method requires an air condenser in one arm of the high-voltage side. The low arms of the bridge are resistances, one arm being shunted by an adjustable air condenser by means of which final balance is obtained. When the bridge is balanced, the following relations exist:

$$\zeta_1 = \frac{C_3}{C_2} Q \; ; \; C_1 = \frac{S}{Q} C_2 \tag{1}$$

Whence, power factor $\simeq$ tan (phase difference)

$$= \omega C_1 \zeta_1 = \omega S C_3 \tag{2}$$

Preliminary measurements with a cylindrical high-voltage air condenser of $8.26 \times 10^{-11}$ farad capacity indicated that for a close balance of the bridge the values of the capacity in the two high arms of the bridge should not differ by a ratio of more than 3 or 4. In view of this fact it was found desirable to construct an air condenser to meet the range of capacities to be found in the samples to be measured. An illustration of the condenser as finally constructed is shown in Fig. 6. It is of parallel plate type having a single central high-voltage plate, 182.88 cm. by 243.84 cm. (6 ft. by 8 ft.), and two low-voltage plates, each 121.92 cm. by 182.88 cm. (4 ft. by 6 ft.), one placed on either side the high-voltage plate. Each low-voltage plate was surrounded by a guard plate 22.86 cm. (9 in.) wide. All metal surfaces were of 0.0396-cm. (0.0156-in.) soft copper, mounted on oak frames, with smooth flat joints, and with edges turned back as indicated in Fig. 6. The low-voltage plates were supported each from its guard plate by six bakelite blocks. The guard plates in their turn were supported by steel rods hung from the upper part of the supporting wooden structure. The entire low-voltage system of each plate was adjustable horizontally permitting a maximum spacing between low-voltage and high-voltage plates of 25.4 cm. (10 in.). The lowest value of spacing used in the experiments was 5.08 cm. (2 in.), thus corresponding to a total range of capacity using both plates of $77 \times 10^{-11}$ farad to $15.4 \times 10^{-11}$ farad. The outside surfaces of the low-voltage plates were screened with copper gauze connected to the guard plates. A 2.54-cm. (1-in.) diameter brass tube extended from the rear of each low voltage plate to the observer's position some 609.6 cm. (20 ft.) away. This tube was also connected to the copper gauze and guard plate. The connections to the low-voltage plates of the condenser were carried through these tubes. The screening system so formed was connected to ground through an adjustable resistance connection, and insulated from ground at all other points. (See Fig. 5.)

The resistances used in the two low arms of the bridge were of Curtis type; that is, specially wound for freedom from capacity and inductance. Each box was placed in its own metal case connected to earth. The resistances used in grounding the various guard circuits were of high grade laboratory type.

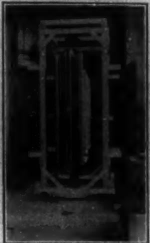

FIG. 6—HIGH-VOLTAGE AIR CONDENSER

The charging currents of the specimens were measured in the ground connections from the test electrodes by means of a Dolacelek quadrant electrometer shunted with resistance and calibrated for voltage in terms of laboratory standards. Suitable switching was arranged so that this electrometer could be used for measuring the current in any section of the bridge connection, including the guard ring circuits of the air condenser, those of the test specimens, and that in the potential divider for measuring the high voltage.

The detecting instrument for balance of the bridge was a Rubens vibration galvanometer with a sensitivity of $6.6 \times 10^{-6}$ amperes per millimeter division in an eyepiece at one meter distance. In the present experiments the instrument was 304.8 cm. (10 ft.) from the observer. The blurring of the sharp image of an incandescent filament indicated unbalance, and it is certain that a much higher sensitivity was reached. No effort was made to estimate a numerical figure for sensitivity of this instrument. Under the best conditions of observation a variation of 0.1 per cent of the adjustable air condenser was sufficient to upset the setting. This variation corresponds to a difference of one figure in the 5th place of a power factor 0.00746. The sensitivity falls off towards the lower range of voltage gradients and lower temperatures, owing to the low values of the loss component of the current. We estimate that in the lowest range of our observations the maximum error in our observations of loss and power factor is not greater than 2 per cent of the values as given.

At a distance 457.2 cm. (15 ft.) beyond the galvanometer and in the same line of vision was mounted a vibrating reed frequency meter with magnified scale having two reeds per cycle. This arrangement, together with close speed control, permitted accurate adjustment of the frequency to the natural period of the vibration galvanometer.

The adjustable air condenser for the final balance of the bridge was of the usual dial type with interleaved plates, one set rotating about a vertical axis, and its position being indicated by a pointer moving over a 180 deg. scale on the top. It was placed in a grounded metal box. This condenser was calibrated in place with its leads and with the guard circuits connected as in Fig. 5, by the Maxwell-Thompson method. The calibration curve is shown in Fig. 7.

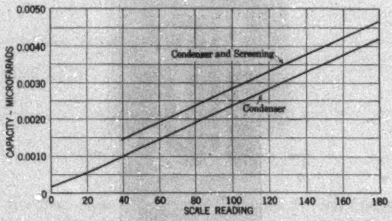

FIG. 7—CALIBRATION CURVE OF CONDENSER AND SCREENING

Mention has been made that the guard rings of both air condenser and test specimen were connected to earth through adjustable resistances. Reference to the diagram of connections, Fig. 5, will indicate the points at which these connections to earth were made. It will be noted that the guard principle was applied to the entire length of the connections from the central electrodes to the center of the bridge by running them in tubes connected to the guard electrodes, and to the rear screen of the central electrodes. The importance of electrostatic screening in work of this character is well understood. We also discovered very early in the tests that it is important that the screening systems and also the guard rings be maintained at the same voltage above ground as that of the central or test electrodes. This was readily accomplished by measuring the currents to earth from test electrodes and from guard rings separately. Then on balancing the bridge a resistance of suitable value could be inserted in the ground connection of the guard ring system. In general not more than two adjustments were necessary to obtain the correct values. In the final condition of balance the resistance in the bridge arm and the resistance to ground in the guard circuit, have values inversely as their respective currents to ground. We believe that in measurements of this character sufficient attention has not been given to the possibilities of stray fields at the ends of or over the leads to the test electrode. In our observations we frequently found that a resistance of several thousand ohms to ground would be necessary in our guard circuit, and that a change of 2 per cent or 3 per cent in the total value of this resistance would be sufficient to throw the bridge out of balance.

## PROGRAM OF TEST

Following is a general statement of the preparation, treatment, and test of the various groups of samples. As a general thing the three samples of one group were carried together through the entire process.

The three samples of each group, equipped with test electrodes and guard electrodes, were first placed in the drying box in which the temperature was slowly raised to 105 deg. cent. A slow draft of air passed through the box. The condition of the samples was observed by absorption and conductivity measurements at 1500 continuous volts. The samples remained in the drying box until there was no further change in their electrical characteristics over a period of twenty-four hours. As a rule this required a total elapsed time of about seventy-two hours. The samples were then transferred while hot to a rack and immediately lowered into the impregnating chamber already heated to 105 deg. cent. The chamber was then sealed, the vacuum pump started, and the pressure reduced to that at which the samples were to be impregnated. In certain cases the pressure was reduced to a minimum of between 1 to 2 mm. Hg. absolute pressure and afterwards allowed to rise to the value for impregnation. The impregnating chamber was kept at the desired pressure and at 105 deg. cent. for two hours and then left to stand over night; usually about fifteen hours. The pressure was readjusted next morning to the proper value and the temperature allowed to fall to 80 deg. cent. The compound already heated to the same temperature was then slowly admitted to the impregnating chamber, the air pressure being maintained approximately constant. After the samples were completely immersed the temperature was maintained for two hours at 80 deg. cent. the pressure remaining unchanged. Air was then admitted to the impregnating chamber and absorption and conductivity measurements made on the samples at atmospheric pressure and 80 deg. cent. The chamber was then allowed to cool over night and the absorption and conductivity measurement repeated at atmospheric pressure and room temperature.

The impregnating chamber was then heated to about 45 deg. cent., the compound drained, and the samples quickly transferred to the high-voltage test box. During this transfer the specimens were in the open air for about five minutes. In the high-voltage test box the samples were immersed in compound. The compound was completely changed for each two groups of samples, three-quarters of the compound being removed for each group, and the fresh compound being that in which the group had been impregnated. In the high-voltage box, measurements were made of total dielectric loss, power factor, and charging current, over a range of temperature from that of the atmosphere to 80 deg. cent., and over a range of voltage of 1.5 to 30 kv., corresponding generally to the range 15 to 300 volts per mil. Usually all three samples were measured in parallel with occasional check measurements on single samples to insure that they were of uniform characteristics.

TABLE I

P. F. MEASUREMENTS. SPECIMENS 3A, 3B, 3C

| Pri. E Ratio 300-1 | Q | S | Cond. rdg. | $C_3$ | Power factor | W. | Temp. air | Deg. cent. spec. | Specimens |
|---|---|---|---|---|---|---|---|---|---|
| 40 | 2000 | 5379.5 | 76.5 | 0.002325 | 0.004710 | 0.6145 | 20.8 | 28.1 | 3A and 3B and 3C |
| 60 | 2000 | 5374.0 | 76.0 | 0.002315 | 0.004695 | 1.379 | 20.5 | 27.6 | 3A and 3B and 3C |
| 80 | 2000 | 5367.0 | 76.2 | 0.002320 | 0.004700 | 2.474 | 20.8 | 27.6 | 3A and 3B and 3C |
| 100 | 2000 | 5359.0 | 78.5 | 0.002365 | 0.004790 | 4.210 | 21.4 | 27.6 | 3A and 3B and 3C |
| 90 | 2000 | 5361.0 | 78.0 | 0.002355 | 0.004760 | 3.345 | 21.4 | 27.6 | 3A and 3B and 3C |
| 20 | 2000 | 5371.0 | 76.0 | 0.002315 | 0.004690 | 0.151 | 21.5 | 27.5 | 3A and 3B and 3C |
| 10 | 2000 | 5371.0 | 75.5 | 0.002300 | 0.004660 | 0.0376 | 21.5 | 27.5 | 3A and 3B and 3C |
| 60 | 2000 | 5365.5 | 76.5 | 0.002325 | 0.004705 | 1.382 | 21.5 | 27.5 | 3A and 3B and 3C |
| 40 | 2000 | 5368.5 | 76.0 | 0.002315 | 0.004690 | 0.6110 | 21.4 | 27.5 | 3A and 3B and 3C |
| 60 | 4000 | 3534.5 | 122.5 | 0.00338 | 0.004500 | 0.4070 | 21.5 | 27.5 | 3A |
| 60 | 4000 | 3565.0 | 130.0 | 0.00355 | 0.004775 | 0.4330 | 21.6 | 27.3 | 3B |
| 60 | 4000 | 3630.0 | 126.0 | 0.00346 | 0.004740 | 0.4380 | 21.2 | 27.0 | 3C |

Following the power measurements, the samples were dipped in paraffin and set aside for further possible tests.

## TYPICAL OBSERVATIONS AND CHECK OF METHOD

The essential measurement is that of power factor, and our measurement of this quantity is based on the final relation of Formula (**2**); that is to say, the balance of the bridge determines the resistance $Q$, the setting and capacity of the adjustable air condenser $C_3$, and also the value of the resistance $S$ in shunt therewith. All of the observations were taken at a frequency of 60 cycles for which value the generator speed could be closely adjusted at each setting, as checked by the amplitude of oscillation of the Hartman and Braun vibrating reed frequency meter. Table I gives a typical set of observations.

The various columns of Table I in their order give the following quantities: The voltage at the low-tension terminals; the resistances of the two low voltage arms of the bridge; the reading of the adjustable air condenser; the corresponding value of the capacity $C_3$; the power factor as computed from Formula (**2**); the total loss as computed from the power factor, the current, and the voltage on the specimen; the temperatures of the outside air and inside the test specimen; and finally, the combination of specimens on which the readings were taken. All measurements were made with a two-circuit, shielded, potential divider connected from high voltage to ground. The value of the high voltage was determined by the current in one circuit of this potential divider, and was at all times found to correspond accurately with the ratio of transformation of the transformer (1-300). The order of the readings in Table I, and the repetition of the readings at different voltages indicates the constancy with which readings are repeated, and also that the three specimens of a single group possess characteristics which are closely similar.

Table II is a sample of the measurements which must be made of the currents in the test and guard circuits of both high-voltage condenser and specimen, at each value of voltage. These readings fix the values of the resistances which must be inserted in the ground connections of the guard circuits in the final condition of balance.

The accuracy of the method was tested by inserting known values of resistance in series with the test samples. In one case the two halves of the high-voltage air condenser were separated, one-half being placed in either high-voltage arm of the bridge. Under these circumstances the adjustable air condenser and all of its connections had to be removed from the bridge in order to secure a balance which was readily accomplished with resistance only in the low arms. A resistance of 12799 ohms was then connected in the low side lead of the central electrode of one of the two high-voltage condensers $C_1$ (Fig. 5). The bridge was

TABLE II

CURRENT MEASUREMENTS. SPECIMENS 3A, 3B, 3C

| Pri. E | $R_1{}^1$ | Zero | Rdg. | Dfln. | I | Circuit |
|---|---|---|---|---|---|---|
| 40 | 400 | 1.58 | 6.05 | 4.47 | $10.85 \times 10^{-3}$ | Tail circuit 3 spec/ in parallel |
| | 1600 | 1.58 | 4.42 | 2.84 | $2.16 \times 10^{-3}$ | Guard circuit 3 spec. in parallel |
| | 1000 | 1.58 | 5.38 | 3.80 | $4.0 \times 10^{-3}$ | Tail circuit H. V. condenser |
| | 1000 | 1.58 | 4.90 | 3.32 | $3.75 \times 10^{-3}$ | Guard circuit H. V. condenser |

then balanced again and the measured value of the power factor was found to be 0.001967. The computed value based on the $I^2 R$ loss in the resistance was 0.001976. Corresponding values using another value (20349 ohms) of series connected resistance were 0.003105 and 0.003140. These constitute a check for values of power factor below the minimum values encountered in our work.

For values in the higher range of power factor a similar series of observations was made using a Moscicki condenser. This condenser is of Leyden jar type immersed in oil and screened against electrostatic influence. The loss in this condenser alone at 12,000 volts was found to be 1.79 watts. With 6003 ohms connected in series the loss was 2.32 watts; the measured difference being 0.53 watts. The computed $I^2 R$ loss in the added resistance was 0.522 watts. A second set of observations at a lower value of voltage gave corresponding figures 0.299 and 0.296 watts. The total power factor in these observations was in the neighborhood of 0.02. This value of power factor is well above most of those encountered in our observations.

The records also show many examples of agreement between the values of loss measured for three samples in parallel and the sum of the values taken on the three samples individually. Table III gives an instance of this.

TABLE III
POWER FACTOR MEASUREMENTS. SPECIMENS 2A, 2B, 2C

| Pri. E. | Q | S | Cond. rdg. | $C_2$ mfd. | Power factor | I | W | Specimens |
|---|---|---|---|---|---|---|---|---|
| 40 | 2000 | 3601.5 | 131.0 | 0.00357 | 0.00485 | $6.6 \times 10^{-3}$ amps. | 0.384 | 3 spec. in par. |
| 40 | 6000 | 3733 | 134.5 | 0.003660 | 0.005150 | $2.21 \times 10^{-3}$ | 0.1367 | 2A |
| 40 | 6000 | 3558.5 | 134.0 | 0.003640 | 0.004890 | $2.15 \times 10^{-3}$ | 0.1261 | 2B |
| 40 | 6000 | 3491 | 136.0 | 0.00368 | 0.004845 | $2.10 \times 10^{-3}$ | 0.1221 | 2C |
| | | | | | | | 0.3849 | for 3 spec. |

The computed value of the capacity of the high voltage air condenser with both halves set at 5.08 cm. (2 in.) spacing is $77 \times 10^{-11}$ farad. The value as determined by the current measured at 15,000 volts in the test electrode circuit on the ground side was $78.4 \times 10^{-11}$ farad. The value of this capacity is needed only for computations of the capacity of the specimens. The latter value was used in these computations.

## EXPERIMENTAL OBSERVATIONS

*The Influence of Moisture in Cable Paper.* We discuss first the influence of different amounts of absorbed moisture on the electrical properties of unimpregnated cable paper. The fact that each set of test samples had to be carefully dried out under exactly similar conditions afforded easy opportunity for studying the progressive change in the absorption and final resistance at different stages throughout the drying period. Provision was made for applying continuous voltage up to 1500 volts to the samples while in the drying box, and for measuring both charge and discharge currents to the test electrode in the usual manner. A Weston D'Arsonval galvanometer of sensitivity of $1.5 \times 10^{-10}$ amperes per division, was used.

The behavior of each group of three samples was much the same throughout the drying period. Individual samples differed in considerable amount in the initial stage, but the shapes of the current-voltage curves, and the types of changes with temperature showed little or no variation among the various sets.

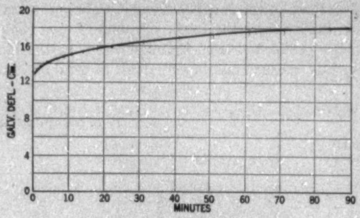

FIG. 8—CHARGING CURVE

Cable paper specimen 1A—110 volts, 20 deg. cent.—Not impregnated

The following description and curves refer to test sample 1-A.

The three samples of group 1, equipped with paper and electrodes, were dried and tested in the impregnating chamber. On test sample 1-A the current through the insulation to the test electrode at 110 volts con-

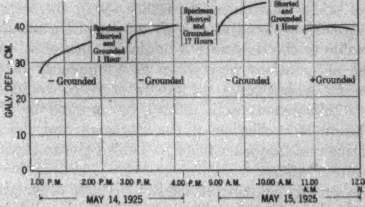

FIG. 9—CHARGING CURVES

Cable paper specimen 1A—110 volts—22.5 to 25.0 deg. cent.—Not impregnated tinuous, and at 20 deg. cent. was as shown in Fig. 8. The current rises continuously for an hour and a half after the first application of voltage, and is not yet constant. After discharging and charging a second time at the same temperature the second curve begins abruptly at approximately the value at which the first curve left off. Much the same effect is observed for a further period of short circuit and charge. After reversal of polarity the current starts at a lower value and seems to decrease slowly. (See Fig. 9.) These results indicate that the continuous application of voltage gives a progressive increase in conductivity, and therefore shows the conspicuous presence of the well-known Evershed effect. All three samples in the group give approximately the same shape of curves, but their ordinates differ amongst themselves. At this temperature (20 deg. cent.) there is only an extremely small indication of residual charge for any of the samples the 30-sec. reading on discharge for 1-A being 5-mm. galvanometer deflection, which may be compared with the corresponding deflection of 40 cm. on charge.

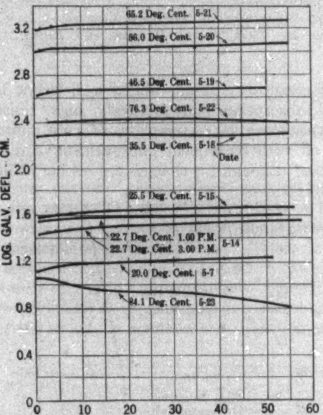

Fig. 10—Current—Time Curves

Cable paper specimen 1A—At various temperatures and 120 volts d-c Not impregnated

The temperature of the samples was then raised in steps of approximately 10 deg. cent. and allowed to come to a steady electrical state at each temperature. The changes in the electrical characteristics follow very closely the changes in temperature. During the process of temperature change it is easily possible to follow the change in the value of the charging current (see Fig. 13). Up to 65 deg. cent. there is a steady and rapid increase of the values of the currents, the curves, however, tending to become flatter (see Figs. 10 and 11). The value of the residual charge also increases through this range, the 30-sec. value reaching 9.2 centimeters at 55 deg. cent. It is still very small as compared with the charging current at the corresponding interval and absorption is as yet not great enough to show itself in the form of the charging current curve. The samples were allowed to stand over night at 75 deg. cent. It was then found that the charging current curve was nearly flat and considerably below that at 65 deg. cent. Thus in this temperature region time enters as a factor. Somewhere between 65 deg. cent. and 75 deg. cent. the conductivity of the sample stops rising and decreases (see Fig. 11). The curve of current on discharge is also correspondingly lower, thus indicating a relation between

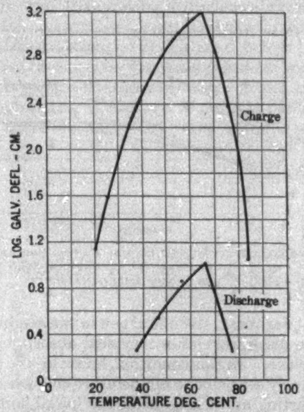

Fig. 11—Charge and Discharge Currents at Increasing Temperature. Unimpregnated Paper

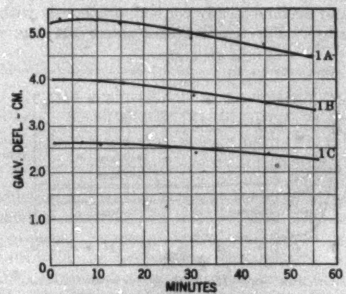

Fig. 12—Charging Curves

Cable paper specimens 1A, 1B and 1C—110 volts, 86.5 deg. cent. Not impregnated absorption and moisture content. It should be noted, however, that the absorption is of negligible magnitude as compared with conduction, up to 75 deg. cent.

At 85 deg. cent. the charging current curves rise slightly at the beginning and then fall off (see Fig. 12). They are still quite flat, but the decrease, although slow, seems to indicate that absorption begins to play its part in the shape of the curve. After standing over night at 90 deg. cent. the initial rise in the charging current curve disappears and a typical absorption curve takes its place. In this condition, however, the paper is still extremely sensitive to temperature change. For example, starting at 94 deg. cent. the initial limb of the absorption curve is readily observed but as the temperature is gradually raised to 103 deg. cent. over a period of two and one-half hours, the current is seen (Fig. 13) to rise and become steady contemporaneously with the temperature. For temperatures above 104 deg. cent. the curves are all of typical absorption type, (see Fig. 14) with little change in shape up to 125 deg. cent. Both absorption and final conductivity continue to decrease in this range suggesting the continued elimination of moisture. Above 85 deg. cent. measurements were made at 500 volts, 1200 volts, and 1500 volts continuous. In all cases, the galvanometer gave deflections in proportion to the voltage and all the curves repeated their shapes.

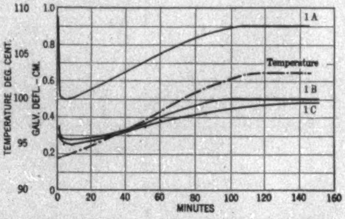

Fig. 13—Charging Curves Cable Paper Specimens 1A, 1B, and 1C with Increasing Temperature—93.5 to 103.0 Deg. Cent.—1500 Volts. Not Impregnated

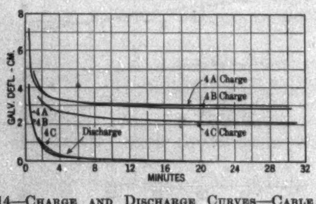

Fig. 14—Charge and Discharge Curves—Cable Paper Specimens 4A, 4B, and 4C—1500 Volts—110.6 Deg. Cent. Not Impregnated

The general conclusion from these studies is that the paper contains large amounts of moisture which are driven off rapidly at 75 deg. cent. or above. Up to this point its conductivity masks the usual dielectric properties. At 105 deg. cent. the paper seems to reach a fairly definite condition. It appears as a dielectric having marked absorption and relatively high resistivity. On further elevation of temperature more moisture is driven off with consequent improvement of dielectric properties, although the changes are neither as marked nor as rapid as in the earlier stages. The properties are quite definite at any one temperature, although there are differences of from 50 to 100 per cent as amongst successive samples tested. Characteristic curves of one group at a temperature of 110.6 deg. cent. are shown in Fig. 14. The final current of specimen

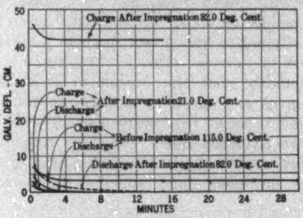

Fig. 15—Charge and Discharge Curves—Cable Paper Specimen 4A—1500 Volts. Before and After Impregnation

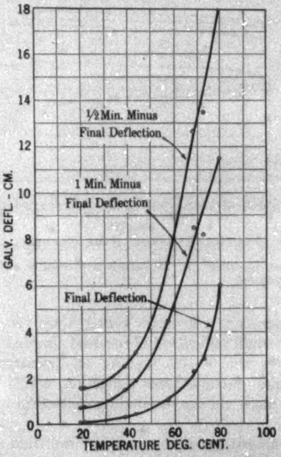

Fig. 16—Absorption and Conductivity—Temperature after Impregnation—Specimens 3B and 3C In Parallel

4-C indicates a resistivity of 1.23 × $10^{-15}$ ohms per cm.[8]

*Influence of Impregnation on Absorption Characteristics.* In preparing the samples for impregnation they were maintained at a temperature of 105 deg. cent. in the drying chamber until they reached a steady state as regards absorption and conduction. Immediately after impregnation at 80 deg. cent. the absorption current values were found to have increased from 40 to 70 times depending upon the sample, although the relative positions of the three curves of the samples of each set remained about the same. The condition is shown in Fig. 15. In this case the increase in absorption current after impregnation is only about 14 times. This is due to the lower temperature (82 deg. cent.) at which the measurements were taken after impregnation. These increases in absorption and in conductivity decrease slowly with time if the sample is maintained at high temperature. There is also some evidence that the application of alternating voltage causes further reductions. The samples apparently reach a uniform condition after one or two days of test. These changes offer an interesting problem for future study.

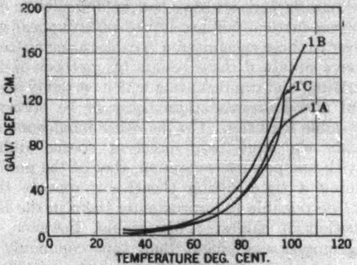

Fig. 17—Charging Current—Temperature after Impregnation. Final Deflection

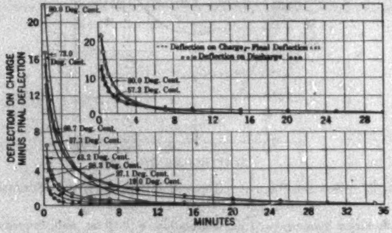

Fig. 18—Absorption—Cable Paper Specimens 3A, 3B, and 3C—In Parallel—After Impregnation—1500 Volts

This large increase in the charging current is almost entirely due to the increased conductivity of the sample, resulting from its impregnation. Figs. 16 and 17 show the rapid increase of both the final and the one minute galvanometer deflections with increasing temperature taken on the samples after impregnation. Obviously the final deflections are measures of the conduction current, and it will be seen that the one-half and the one minute deflections increase at much the same rate. Furthermore, the residual charge, as indicated by the discharge curves, shows relatively a much smaller increase than the conduction current. This is shown in Fig. 15 in which the discharge curve after impregnation and at 82 deg. cent. is seen to lie only slightly higher than the curve for 21 deg. cent. before impregnation. Fig. 18 shows for various temperatures the difference between the final steady deflection and the deflection taken at intervals during the charging period. These curves therefore show the total current minus the conduction current that is to say, the so-called reversible anomalous current. It will be seen that with the exception of the curve at 80 deg. cent. the absorption increases with the temperature throughout. The inset on Fig. 18 compares the reversible anomalous current on charge with the current on discharge, for temperatures 80 deg. cent. and 57 deg. cent. It will be seen that at each temperature the two curves are closely coincident which again indicates that the large increase in the charging current curves after impregnation is due to the increased conductivity caused by the presence of impregnating material. Moreover, this seems to be a uniform conductivity as that portion of the charging current curve due to absorption is completely reversible.

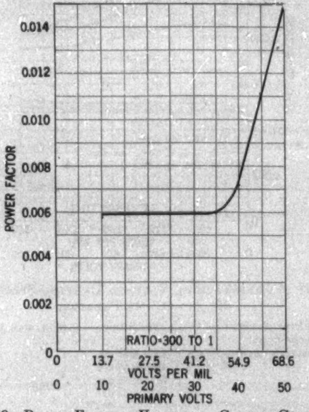

Fig. 19—Power-Factor—Voltage Curve—Commercial Cable "A"—4000-Volt, Three-Conductor, No. 6

4/32 in. by 3/32 in. insulation—measured in air on 4 ft. of cable—21.5 deg. cent.

The conclusion from these observations is that the conductivity of cable paper is greatly increased on impregnation. There is also a corresponding increase in the dielectric absorption. The increased conductivity falls off rapidly with the temperature and at 20 deg. cent. approaches that of the dry unimpregnated paper. The conductivity thus introduced by the compound seems to be constant in character at any one temperature and to possess the irreversible character often observed in liquid dielectrics. A further study is planned of the characteristics of paper and compound separately and in combination, under different conditions of impregnation.

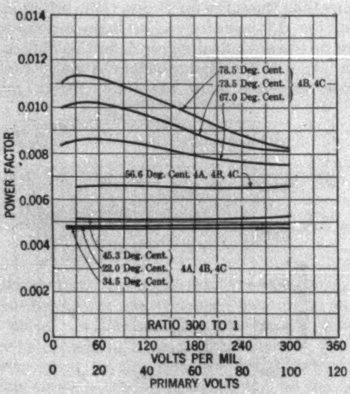

Fig. 20—Power-Factor—Voltage Curves—Specimens 4A, 4B, and 4C—In Parallel

Conductor diameter = 1 in. Insulation = 0.10 in. wall, impregnated at 2-mm. pressure

Conductivity in dried state = 4A—3.40 cm.
4B—3.45 cm.
4C—2.55 cm.

*The Influence of the Air Pressure at Impregnation.* The first purpose of our experiments has been the study of the influence of the air pressure at which impregnation takes place, on the shape of the power-factor—voltage curve. The sharp break often observed in this curve, (as for example in Fig. 19), is generally attributed to the presence of air in thin layers which breaks down to cause increased loss, when the voltage gradient rises above a certain value. It does not appear to be clearly determined, however, whether or not these air layers are generally distributed through the successive layers of paper. If so a variation of the air pressure at which impregnation takes place might have an influence on the shape of the power-factor curve. It may be said here that the evidence from our experiments indicates that the break in the power-factor curve is far more often to be traced to a definite air layer between insulation and a loose fitting sheath, rather than to air films distributed through the body of the insulation.

The air pressure at impregnation apparently plays a more important role in its action in facilitating the driving off of still further residual moisture, after the greater part has been driven off under preliminary temperature drying. It appears to be impossible to completely expel all moisture from cable paper. Final temperature and air pressure, and the time during which they are applied are the principal factors determining the ultimate state of the paper. Extending the ranges of these factors well beyond the values used in cable manufacture we have had no difficulty in obtaining power-factor—voltage curves which appear greatly superior to those encountered in cables as manufactured. We have obtained these results by methods of drying, evacuating, and impregnating which certainly are more careful and prolonged than those to be observed in many cable factories. On the other hand none of the methods we have used involves special difficulty, and with one possible exception, that of the method of obtaining a tight fitting sheath, it appears that it should be possible to approximate them in the factory production of cables. They would, however, entail more complex equipment than that commonly used, and more time, thus increasing costs considerably. One manufacturer has stated that he can duplicate our flat power-factor curves in cables for the market if the purchaser will stand for the additional price.

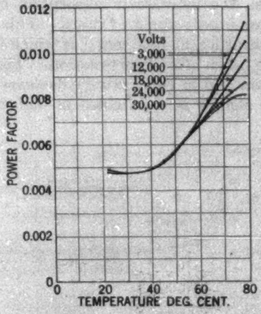

Fig. 21—Power Factor—Temperature Curves—Specimens 4A, 4B, and 4C in Parallel

Conductor diameter = 1 in. Insulation = 0.10 in. wall, impregnated at 2-mm. pressure

The results of our study of the influence of the air pressure at impregnation are shown in the series of curves of Fig. 20 to 38. The range of pressure studied is from 2 mm. to 76 cm. Hg. absolute pressure, extending well beyond the range used in manufacture, in both directions.

There are several striking results to be noted from this series of curves:

*Characteristics of Thorough Impregnation.* The characteristic type of the power-factor-voltage curve for complete impregnation is exemplified in Fig. 20 for 2 mm. impregnating pressure. Up to 56 deg. cent. the power-factor curves are perfectly flat over the range 30 to 300 volts per mil. At higher temperatures the curves show increasing maxima in the neighborhood of the relatively low gradient 40 volts per mil and apparently tending to become flat towards the upper range. Although the values of the power factor may vary from one set of curves to another this typical shape is remarkably well preserved over the range of pressure 2 mm. to 10 cm.

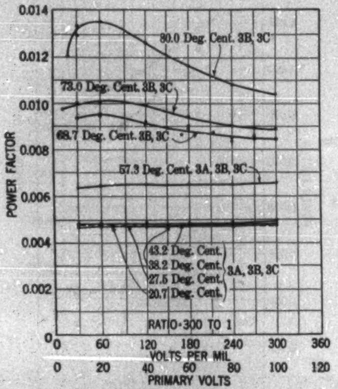

Fig. 22—Power-Factor—Voltage Curves—Specimens 3A, 3B, and 3C in Parallel

Conductor diameter = 1 in. Insulation —0.10 in. wall, impregnated at 5-mm. pressure

Conductivity in dried state = 3A—0.65 cm.
3B—0.63 cm.
3C—0.57 cm.

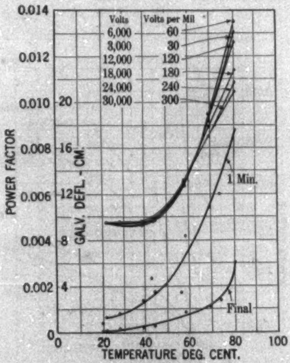

Fig. 23—Power Factor—Temperature Curves—Specimens 3A, 3B, and 3C in Parallel

Conductor diameter = 1 in. Insulation = 0.10 in. wall, impregnated at 5-mm. pressure

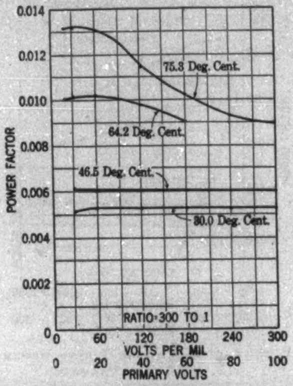

Fig. 24—Power-Factor—Voltage Curves—Specimens 12A, 12B, and 12C in Parallel

Conductor diameter = 1-in. Insulation = 0.10 in. wall, evacuated and impregnated at 1-cm. pressure

Conductivity of dried specimens about twice normal due to high humidity

Conductivity in dried state = 12A—8.3 cm.
12B—8.1 cm.
12C—6.8 cm.

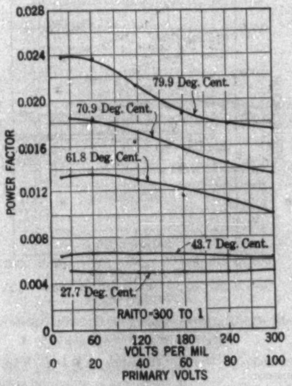

Fig. 25—Power-Factor—Voltage Curves—Specimens 10A, 10B and 10C in Parallel

Conductor diameter 1-in. Insulation = 0.10 in. wall, evacuated and impregnated at two-cm. pressure

Conductivity of dried specimens about six times normal due to high humidity

Conductivity in dried state = 10A—19.0 cm.
10B—20.0 cm.
10C—16.0 cm.

*Pressure Range for Thorough Impregnation.* Over the range of pressure 2 mm. to 10 cm. Hg. pressure the flat power factor curve of the lower range of temperature appears throughout. There is no evidence within the range of air pressures mentioned of a break followed by sharply rising values in the power-factor–voltage curve. This seems to indicate that with sufficient care to obtain thorough drying, impregnation, and close fitting sheath, internal gaseous ionization may be eliminated and good power factor curves obtained without

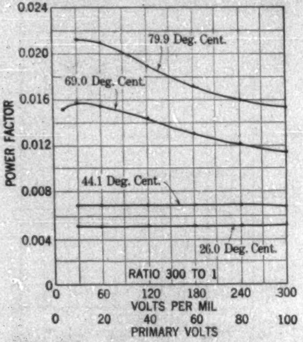

Fig. 26—Power-Factor—Voltage Curves—Specimens 11A, 11B, and 11C in Parallel

Conductor diameter = 1.0-in. Insulation 0.10-in. wall, evacuated and impregnated at 3 cm. pressure

Conductivity of dried specimens about three times normal due to high humidity

Conductivity in dried state = 11A—8.7 cm.
11B—4.6 cm.
11C—6.2 cm.

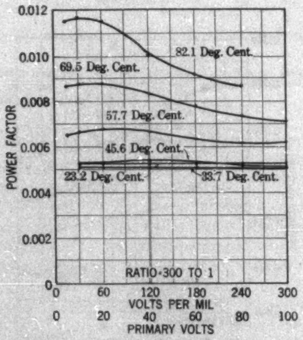

Fig. 27—Power-Factor—Voltage Curves—Specimens 8A, 8B, and 8C in Parallel

Conductor diameter = 1-in. Insulation = 0.10 in. wall, evacuated to 2-mm. pressure

Impregnated at 5-cm. pressure

Conductivity in dried state = 8A—4.00 cm.
8B—2.70 cm.
8C—1.80 cm.

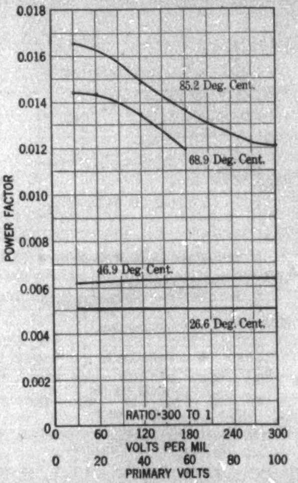

Fig. 28—Power-Factor—Voltage Curves—Specimens 14A, 14B, and 14C in Parallel

Conductor diameter = 1-in. Insulation 0.10-in. wall, evacuated and impregnated at 5-cm. pressure

Conductivity in dried state = 14A—2.30 cm.
14B—1.75 cm.
14C—1.35 cm.

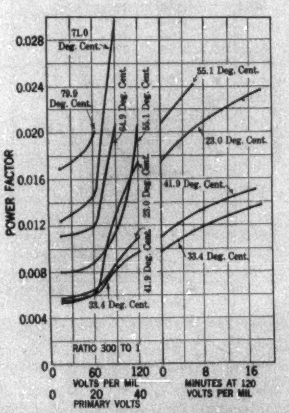

Fig. 29—Power-Factor—Voltage—Power Factor—Time—Specimen 6A

Conductor diameter = 1-in. Insulation 0.10-in. wall, impregnated at 5-cm. Hg.

Conductivity in dried state—3.35 cm.

the necessity of an evacuation pressure lower than 10 cm. Hg. Or stated more briefly, complete impregnation of cable paper, without resulting gaseous ionization, or rising power-factor–voltage curve, may be obtained at air pressures of impregnation up to 10 cm. Hg.

A single exception to the foregoing is illustrated by Fig. 29, giving results on a set of specimens evacuated and impregnated at 5-cm. pressure. This set of curves shows the typical ionization power factor curve; *i. e.*, a sharp break followed by rapidly ascending values. These curves were taken in a series of studies with ascending values of impregnation pressure. At first they seemed to indicate that a critical pressure causing

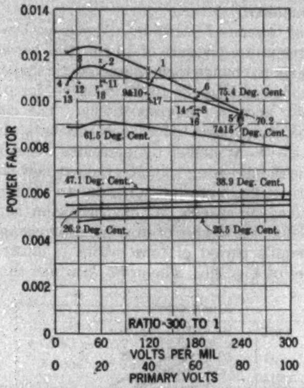

Fig. 30—Power-Factor—Voltage Curves—Specimens 9A, 9B, and 9C

Evacuated to 3-mm. pressure
Impregnated at 10-cm. pressure
Numbers at points indicate order in which they were taken
Conductivity in dried state = 9A—3.95 cm.
9B—3.95 cm.
9C—2.55 cm

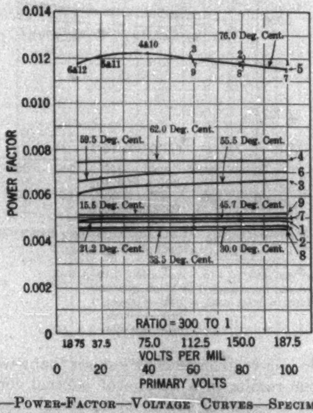

Fig. 31—Power-Factor—Voltage Curves—Specimens 2A, 2B, and 2C in Parallel

Conductor diameter = 1 in. Insulation, 0.16-in. wall.
Evacuated to 3.5-cm. pressure
Impregnated at 10-cm. pressure
Drying period abnormally long
Numbers at curves indicate the order in which they were taken
Conductivity in dried state = 2A—2.05 cm.
2B—1.22 cm.
2C—1.42 cm.

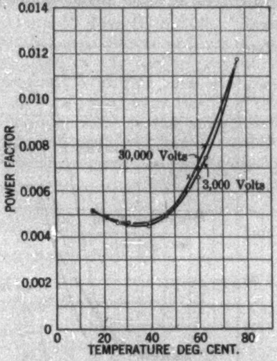

Fig. 32—Power-Factor—Temperature Curves—Specimens 2A, 2B, and 2C in Parallel

Conductor diameter = 1 in. Insulation, 0.16-in. wall

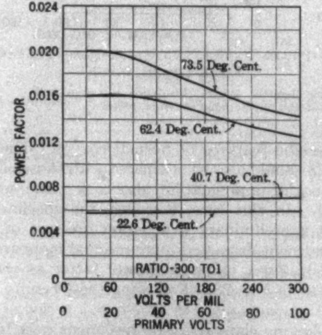

Fig. 33—Power-Factor—Voltage Curves—Specimens 13A, 13B, and 13C in Parallel

Conductor diameter = 1-in. Insulation, = 0.10-in. wall
Evacuated and impregnated at 10-cm. pressure
Conductivity in dried state = 13A—3.60 cm.
Drying period—192 hrs. 13B—3.85 cm.
13C—3.25 cm.

internal ionization had been reached. On going to higher pressures, however, the normal flat curves were again observed. Another set of specimens was therefore constructed, dried, evacuated, and impregnated under the same conditions as those of set No. 6 shown in Fig. 29. The results of this duplicate set No. 14 are shown in Fig. 28 and as will be noted they indicate perfectly flat curves at lower temperatures and other characteristic features of normal curves. The curves of Fig. 28 should also be compared with those of Fig. 27 in which the impregnation also took place at 5-cm. pressure. In this case, however, the specimens had received a preliminary evacuation pressure of 2 mm. This treatment extracted more residual moisture which resulted in lower values of power factor as compared with those of Fig. 28. Following these results further observations were made in set No. 6, a period of several months having elapsed. The specimens were found to still possess their original characteristics as shown in Fig. 29. It is evident, therefore, that in the sharp difference of behavior of these two sets prepared apparently in the same manner, we should find very direct evidence as to the cause of the ascending power-factor curve. In a subsequent series of accelerated life tests the specimens of set No. 6 all showed much shorter life than those of set No. 14. In stripping the specimens those of set No. 6 were found to contain large amounts of entrained air between layers, while those of set No. 14 were almost devoid of traces of air. We conclude, therefore, that for some reason which we can not explain, perhaps for example, the priming of the compound, this set of specimens did not receive complete impregnation. No other instance of this difficulty was encountered.

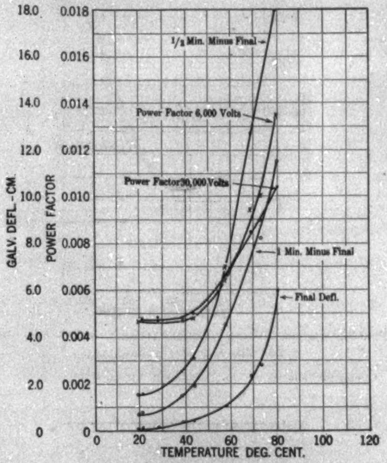

Fig. 34—Power Factor and Absorption—Temperature—Specimens 3B and 3C

Conductor diameter = 1-in. Insulation = 0.10-in. wall
Evacuated and impregnated at 5-mm. pressure

*Internal Gaseous Ionization.* Above an evacuation and impregnation pressure of 10 cm. the power-factor curves begin to change their characteristic shape. This is exemplified in Figs. 35 to 38 inclusive, for pressures 15, 25, 40, and 76 cm. respectively. The curves at low temperatures begin to lose their horizontal character and the curves at higher temperatures instead of decreasing with increasing voltage gradient now show the characteristic sharp upward turn, due to the ionization of the internal air spaces. Within this region there is also evidence that the degree of impregnation changes over a considerable period of time. This is illustrated in the curves of Fig. 36. The order in which the curves are taken is indicated and clearly shows that a temperature cycle results in a change of internal condition. This period seems to extend over several days, after which time there is some suggestion that the specimens reach a steady and improved condition. Some of the specimens in this range have been stripped and all show the presence of copious air spaces.

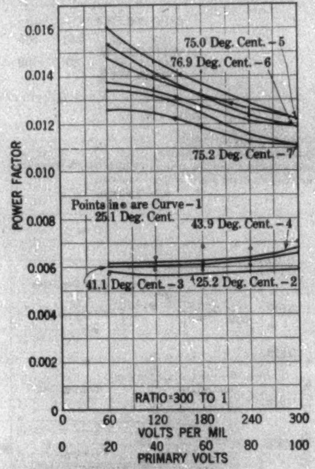

Fig. 35—Power-Factor—Voltage Curves—Specimens 19A, 19B, and 19C in Parallel

Conductor diameter = 1 in. Insulation, 0.10-in. wall
Evacuated and impregnated at 15 cm. pressure
Conductivity in dried state = 19A—2.00 cm.
19B—1.50 cm.
19C—3.60 cm.

We show elsewhere that a layer of air between insulation and sheath is a very probable cause of gaseous ionization. It may be seen, therefore, that even with thorough impregnation of the insulation, gaseous ionization may still exist between the insulation and sheath and reflect itself in the characteristic upward break in the power-factor—voltage curve.

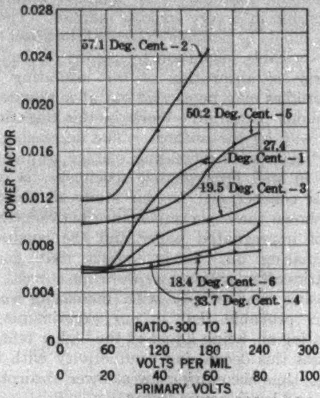

FIG. 36—POWER-FACTOR—VOLTAGE CURVES—SPECIMENS 17A, 17B, AND 17C IN PARALLEL

Conductor diameter = 1 in. Insulation = 0.10-in. wall
Evacuated and impregnated at 25-cm. pressure
Conductivity in dried state = 17A—2.25 cm.
17B—1.60 cm.
17C—1.55 cm.

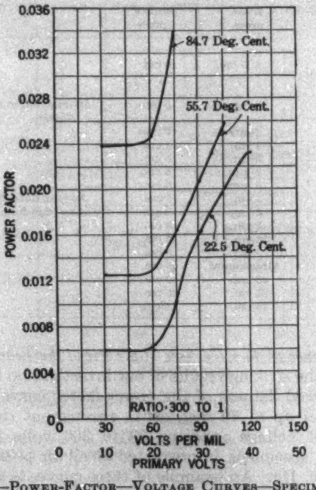

FIG. 37—POWER-FACTOR—VOLTAGE CURVES—SPECIMENS 16A, 16B, AND 16C IN PARALLEL

Conductor diameter = 1 in. Insulation, 0.10-in. wall
Evacuated and impregnated at 40-cm. pressure
Conductivity in dried state = 16A—3.15 cm.
16B—2.85 cm.
16C—2.10 cm.

*Influence of Residual Moisture.* Although as already noted the power-factor—voltage curves have a typical shape for all pressures, up to 10 cm., it will be observed that some of the specimens show very much higher values of power factor than others, as for example, sets Nos. 11 and 13, Figs. 26 and 33. These differences are apparently due to excess amounts of residual moisture. As stated in the earlier part of the paper a definite program of drying and evacuation was determined and followed, with the idea that it would bring all the specimens to the same initial condition. A quite different result was found. Table 4 gives the drying period and temperatures of the various specimens together with, in columns 4, 5, and 6 the values of their final conductivities after drying, this latter being expressed in terms of galvanometer deflections. The wide range of variation is at once evident. It is chiefly caused by the variation in the atmospheric humidity. In the drying period the specimens are heated in the presence of a slow draft of air, as already described. At very high values of atmospheric humidity, during the summer months, it was impossible even in prolonged periods of drying to reduce the conductivity below the very high values indicated by specimens Nos. 10, 11, and 12. The curves of specimens Nos. 10, 11, and 12 especially seem to indicate that residual moisture will cause higher values of power factor without materially changing the shape of the curve. If, however, the pressure is carried down sufficiently low, say to 1 cm. Hg., this may offset the imperfect drying conditions and

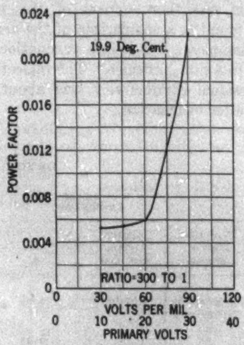

FIG. 38—POWER-FACTOR—VOLTAGE CURVES—SPECIMENS 15A, 15B, AND 15C IN PARALLEL

Conductor diameter = 1 in. Insulation, = 0.10-in. wall
Evacuated and impregnated at 76-cm. pressure
Conductivity in dried state = 15A—1.95 cm.
15B—3.25 cm.
15C—4.25 cm.

result in a power-factor curve of normal shape and value. It appears evident that our preliminary drying period—72 hours at 105 deg. cent. in a slow draft of air at atmospheric pressure,—is very thorough. The subsequent treatment as regards evacuation has relatively small influence up to 10-cm. evacuation pressure. The power-factor–voltage curves all retain their shape. Such differences as appear are principally in the absolute values of power factor at the higher temperatures. These increases are always to be explained either by high atmospheric humidity or higher values of pressure at evacuation. These increases in power factor never assumed serious proportions. For example, as regards pressure of evacuation, the difference between 2 mm. and 5 cm. is reflected in an increase of the maximum power-factor from 0.012 to 0.017. At 10-cm. evacuation the power factor is of the order of 0.02. Another indication of the thoroughness of the preliminary drying was found in a comparison of the absorption of one set of samples taken before evacuation and after evacuation to 4-mm. pressure. The dielectric absorption and residual conductivity was about the same before and after evacuation.

TABLE IV

DRYING AND IMPREGNATION HISTORIES

Sets 2–19

| Set no. | Drying data | | | | | Impregnation data | | |
|---|---|---|---|---|---|---|---|---|
| | Time after start of drying | Approx. temp. deg. cent. | Final deflection | | | Evac. press | Impreg. press | |
| | | | A | B | C | | | |
| 2 | Just before impregnating Drying very long. | 102-103 | 2.05 | 1.22 | 1.42 | 3.5 cm. | 10 cm. | |
| 3 | 96 | 105 | 0.65 | 0.63 | 0.57 | 5 mm. | 5 mm. | Overheated to 160 deg. for 30 min. |
| 4 | 72 | 100 | 3.40 | 3.45 | 2.55 | 2 mm. | 2 mm. | |
| 5 | 72 | 106 | 2.38 | 2.20 | 1.65 | 1 cm. | 1 cm. | |
| 6 | 72 | 106 | 3.35 | 3.00 | 1.85 | 5 cm. | 5 cm. | |
| 8 | 72 | 106 | 4.00 | 2.70 | 1.80 | 2 mm. | 5 cm. | |
| 9 | 72 | 105 | 3.95 | 3.95 | 2.55 | 3 mm. | 10 cm. | |
| 12 | 72 | | 8.30 | 8.10 | 6.80 | 1 cm. | 1 cm. | Drying data doubtful due to high humidity. |
| 10 | 96 | | 19.0 | 20.0 | 16.0 | 2 cm. | 2 cm. | |
| 11 | 72 | | 9.70 | 4.60 | 6.20 | 3 cm. | 3 cm. | |
| 13 | 192 | 107 | 3.60 | 3.85 | 3.25 | 10 cm. | 10 cm. | |
| 14 | 72 | 104 | 2.30 | 1.75 | 1.35 | 5 cm. | 5 cm. | |
| 15 | 96 | 104 | 1.95 | 3.25 | 4.25 | Atmosphere | 45 cm. | |
| 16 | 72 | 103 | 3.15 | 2.85 | 2.10 | 40 cm. | 40 cm. | |
| 17 | 72 | 103 | 2.25 | 1.60 | 1.55 | 25 cm. | 25 cm. | |
| 19 | 72 | 104 | 2.00 | 1.50 | 3.60 | 15 cm. | 15 cm. | |

*Influence of Absorption and Conductivity.* Throughout our measurements, we have taken closely parallel readings of power factor and of conductivity and dielectric absorption at 1500 volts continuous. The curves of Fig. 34 specimens 3-B and 3-C, show the variation with temperature of the power factor, of the final conductivity, and of absorption, as indicated by the one-half minute and one minute readings of the charging current curve. The similarity of form of the power factor and absorption curves is very striking. It has been recognized since the early work of Hopkinson, Rowland, and Hess and from subsequent refined laboratory studies that there is an intimate connection between the dielectric loss and dielectric absorption. The curves of Fig. 34 emphasize this relationship in a very striking manner. They suggest that it should be possible to control the losses and power factor in cable insulation by means of studies of the property of absorption of the insulating materials. Such studies may be carried out at moderate values of continuous potential. Work in this direction is now under way by the authors. The decreasing values of power factor with increasing voltage gradients, always found in well impregnated specimens, is of interest in this connection. In our study of absorption we have shown the close importance between the absorption of impregnated paper and the conductivity of impregnating oil. It is known that good liquid dielectrics often evidence a saturation current that has a decreasing conductivity with increasing voltage. It appears probable that in our experiments, the impregnating oil, being liquid at the higher temperatures, possesses this decreasing conductivity with increasing voltage, thus accounting for a lower absorption, lower losses, and lower power factor.

*Influence of the Closeness of the Fit of the Lead Sheath.* One of the striking results of our investigation has been the marked flatness of the power-factor curve at temperatures up to 60 deg. cent., throughout the entire range of voltage gradient 30 to 300 volts per mil, and for specimens impregnated at all air pressures up to 10 cm. Hg. An example of these curves is shown in Fig. 22.

Examples of curves observed on commercial cables having approximately the same type of insulation are shown in Figs. 19 and 39. In looking for possible causes of these marked differences between our specimens constructed in the laboratory and those taken from cables manufactured by commercial methods, we noticed the relatively loose fit which the sheathing of the commercial cables makes with the underlying cable paper insulation. This condition was perhaps accentuated by the cutting and stripping of the lead in order to provide test electrodes necessary in samples of short lengths. In our methods of test the electrodes, which correspond to the lead sheath, were applied to the cable before impregnation. It thus appeared desirable to study the question as to the influence of air lying between the outer wall of insulation and the lead sheathing. With this purpose in view, samples A and C of set No. 5 of our series were equipped with electrodes before impregnation in the regular manner. Sample B was impregnated before the electrodes were applied. The electrodes were applied first loosely and afterwards tightly.

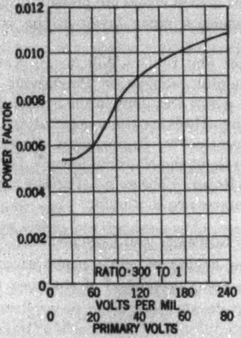

Fig. 39—Power-Factor—Voltage Curve—Commercial Cable "B"—Specimens A, B, C, Measured in Parallel in Compound

500,000 cir. mil conductor
Insulation, 0.10-in. wall—7/8 in. × 0.0065 paper—22.5 deg. cent.

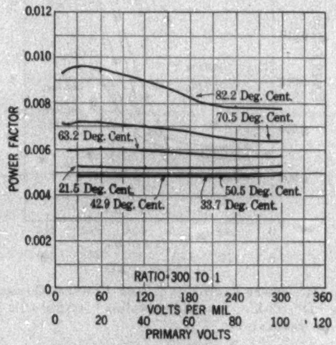

Fig. 40—Power-Factor—Voltage Curves—Specimens 5A, 5C in Parallel

Conductor diameter 1 in. Insulation, = 0.1-in. wall
Impregnated at 1-cm. pressure

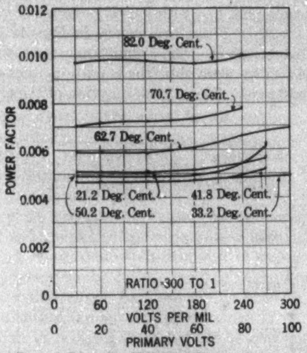

Fig. 41—Power-Factor—Voltage Curves—Specimen 5B—Loose Sheath Applied After Impregnation Tests Under Compound

Conductor diameter = 1 in. Insulation = 0.1-in. wall
Impregnated at 1-cm. pressure

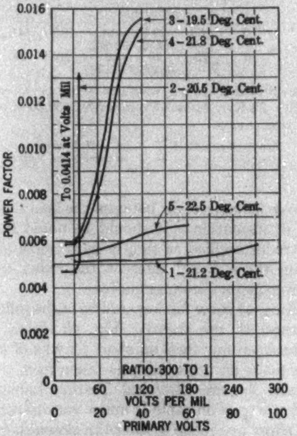

Fig. 42—Power-Factor—Voltage Curves—Specimen 5B—Influence of Tightness of Sheath

Fig. 40 shows the observations on 5-A and 5-C and Fig. 41 shows the observations on specimens 5-B; the observations being taken under compound. It will be noted that there is a pronounced influence of the loose electrode in causing the power-factor curves to turn upward at all temperatures. By far the most striking indication of the influence of a loose application of the sheath after impregnation is shown by the observations on 5-B taken in the air, that is, not under compound, and with varying degrees of tightness of the sheath. These are shown in Fig. 42. These curves were taken with conditions approximately, as closely as we were able, the conditions that are met in manufacture. There is no question of the great importance of the layer of air between the lead sheath and the wall of insulation. It should be noted that with test electrodes applied as tightly as possible after impregnation there is still present the rising tendency of the power-factor—voltage curves.

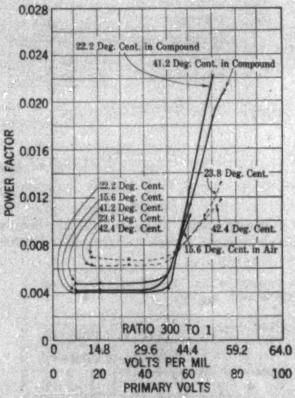

Fig. 43—Power-Factor—Voltage Curves—Commercial Cable "C"—22-Kv., Single-Conductor, 500,000-Cir. Mils. 13/32-In. Insulation

Measurements by E. T. L. on 13-ft. lengths
Measurements by J. H. U. on three-20-in. lengths

Figs. 43 and 44 show further studies of the influence of the tightness of the sheath. Fig. 43 shows a comparison between our tests on short lengths of cable C, and tests made on other samples taken from the same lot of cable by the Electrical Testing Laboratories. Fig. 44 shows tests on cable D under various conditions in which effort was made to alter the closeness of the fit between sheath and insulation. Strapping down tightly the ends of the lead sheathing, removing same and applying a tight electrode by our methods, and bending the sample in various ways changes the performance very little. The fact that these curves were all taken under compound, which from our experience, always tends to keep the curves at their nearest approach to horizontal form, again indicates that air between the sheathing and the insulation plays an important part in causing the break of the power-factor curve away from the horizontal.

The several measurements, described above, all seem to indicate clearly the influence on the power-factor curve of an air layer between lead and paper. This does not necessarily mean that deeper lying films of air may not play their part. On the contrary, it indicates that if such layers are present they, too, must necessarily cause a rising break in the power-factor curve.

Thanks are due to Dr. William B. Kouwenhoven for much helpful cooperation throughout the course of the work which was done in the School of Engineering, The Johns Hopkins University, at the request of the Subcommittee on Impregnated Paper Insulated Cable Research, of the National Electric Light Association, D. W. Roper, Chairman. Further studies under the same auspices are continuing.

## Summary and Conclusions

1. In the drying of cable paper at atmospheric pressure the great proportion of absorbed moisture is given off between 75 deg. and 80 deg. cent. At lower temperatures, the electrical conductivity under the continued application of voltage increases with time in accordance with the Evershed effect. At higher temperatures the paper takes on the characteristics of a highly absorbent dielectric.

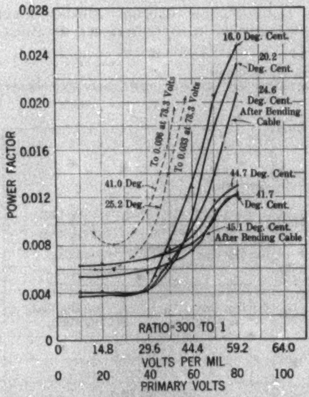

Fig. 44—Power-Factor—Voltage Curves—Commercial Cable "D", 22-Kv., Single-Conductor—500,000 Cir. Mils. 13/32-In. Insulation

Measurements by E. T. L. on 15 ft. length
Measurements by J. H. U. on 3-20 in. lengths

2. In drying by elevation of temperature the final steady state of the paper depends on the temperature,

the time, and on the relative humidity of the atmosphere. Similar examples carried through the same drying process but at different times may have widely different residual moisture and electrical properties. A drying period of 72 hr. at 105 deg. cent. in a dry atmosphere renders cable paper an excellent insulator, although it still contains moisture and shows high dielectric absorption.

3. The evacuation process following that of temperature drying is principally important as removing still further residual moisture. It is not, however, so important in this particular as the initial drying period. Differences in the humidity of the initial drying period show themselves through subsequent evacuation periods at 1, 2, and 3 cm. Hg. pressures, and above.

4. After impregnation, the conductivity and absorption are greatly increased at the higher temperatures, but near atmospheric temperature the values are approximately the same as for the dry unimpregnated paper. The differences are apparently due to the conductivity of the impregnating compound.

5. Using a drying and evacuating and impregnating period of four days we have found for all pressures of impregnation up to 10 cm. Hg., and for temperatures up to 50 deg. cent. power-factor–voltage curves which are perfectly flat over the range 20 to 300 volts per mil, at values in the neighborhood of 0.005. At higher temperatures, the curves are higher and show maxima near 45 volts per mil, the power factor *decreasing* steadily thereafter with increasing stress.

6. Up to 10 cm. Hg., impregnating pressure differences in the original state of the samples as regards moisture reflect themselves in small changes in the values of final power factor without material influence on the shape of the curves. High moisture content increases the power factor.

7. Up to 10 cm. Hg., the pressure of impregnation causes no tendency of the power-factor curve to break and rise, usually attributed to gaseous ionization. Above 10 cm. pressure rising power-factor curves appear, reaching the typical ionization shape at 25 cm. pressure.

8. Typical gaseous ionization curves have been obtained and controlled by variations in the tightness of the lead sheath or test electrodes. It appears that the rising power-factor curves found in cables are in all probability due either to loose fitting sheaths or to imperfect impregnation, causing extended layers of air rather than to original entrained air as dependent on the evacuation pressure.

9. Power factor and dielectric absorption follow similar curves and the latter is suggested as a promising method for the predetermination of the properties of cable insulation.

# The Electric Arc and its Function in the New Welding Processes

BY P. ALEXANDER[1]

Member, A. I. E. E.

**Synopsis.**—*The subject of this paper is a phenomenon of great interest and very great complexity. The electric arc is a tool of extreme power and flexibility. The electric arc can be used to melt the most refractory substances, cut the armor plates of battleships or weld together the ends of wires no thicker than a human hair. It is a wonderful tool that makes or breaks almost anything. It may unite the most indifferent elements such as nitrogen and oxygen, or break the molecule into its constituent atoms.*

*In this paper we shall discuss only one type of application of the electric arc; namely, the application of the arc to the welding of metals, but even in these limits the field is very wide.*

*The electric arc was discovered by H. Davy who in 1810 was experimenting with the sparking between two horizontally disposed carbon pencils. The density of the current was such that on short circuit the tips of the carbon pencils were heated to incandescence. When the electrodes were separated the electric current continued to flow across the air-gap between the carbon pencils. The air-gap was bridged by some sort of an extremely bright band which under action of the accending currents of hot air was bent upwards and formed a bow or an "arc." This is the origin of the term, the "electric arc."*

*For many years the electric arc was used only as a source of light. It was only years later that the electric arc was applied for the purpose of melting and welding metals together. In 1881 de Meritens for the first time used a small carbon arc for melting and welding the lead terminals of storage batteries. The more extensive application of the carbon arc was done by Bernardos.*

*This process was modified by Dr. Zerener of Berlin, Germany, who shortly prior to 1890 invented a process of welding with a flaming arc. In this process two carbon electrodes are disposed to form a "V". The arc is drawn between the two electrodes and caused to impinge upon the metal to be welded by being forced down by a powerful electromagnet. This arrangement caused the arc to act in a similar manner to the flame of an oxyacetylene flame. The energy developed in this arc is only partly transmitted into the weld and the efficiency of the method is very low.*

*The third type arc welding known now as a metallic arc process was discovered about 1890 by H. Slawianoff.*

*This engineer conceived the idea of producing steel ingots by an electrical casting process. Metal was deposited from a steel rod into a mold, an electric arc being maintained between the rod and the metal of the mold. Means were provided whereby the metal rod could be fed forward as it was consumed and a solenoid arrangement was provided for maintaining the arc length substantially constant. The ingots obtained under such conditions proved to be sound and free from shrinkage pipes. However, the cost of electrical energy in Russia in those days was very high and the process was commercially uneconomical.*

*The information obtained by Slawianoff in this work led to the application by him of the metallic arc to the uniting together of metal plates, the repairing of cracked and broken machines, etc.*

*Thanks to the work of Slawianoff we now possess a method of welding with metallic electrodes which at present is by far the most used of all arc welding processes.*

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## ELECTRIC ARC

THE metallic welding arc is a phenomenon of great complexity. It is a combination of three distinct features; namely, conduction of the electric current, melting of the plate, and deposition of the metal from the rapidly melting electrode. The first feature in itself is a complicated phenomenon, which can be understood better if we consider it after reviewing the accepted ideas on electric conduction in solid conductors and in vacuum tubes.

The electric current flowing through the solid conductor has been demonstrated by the experiments of Talman and Stewart to consist wholly of electrons. The positive ions form a rigid frame-work and participate only in the vibratory movements due to the thermal agitation. The whole space is occupied by the spheres of action of the atomic forces. And between atoms there is a continual exchange of the electrons. At any instant there is a number of electrons in transition from one atom to another. These dartings from one atomic system into another are especially numerous in good conductors, and the electrons which during that short flight do not belong to any atomic system are termed free electrons. In the absence of an electromotive force, these movements are equally distributed in all possible directions, and the resultant of those elementary currents is zero. When a difference of potential is, however, impressed on the conductor, these disorderly migrations acquire a certain orientation so that more electrons will be moving in the direction of the positive pole.

An idea of the number of moving electrons may be obtained if we will try to visualize the number $1.6 \times 10^{19}$ which represents the number of electronic dartings during one second through the cross-section of the conductor when it is carrying a current of one ampere. However great this number may seem, it is not the total number of electronic dartings but only a difference between those directed towards the positive and negative poles.

The conduction through the space not occupied by the solid conductor is electronic only in case of extremely high vacuum. In this case the electrons shoot from the cathode in straight lines across the empty space between the comparatively few molecules present which in extremely high vacuum can be in the order of a hundred million per cubic centimeter. Since the molecules themselves are mostly an empty space with a few specks representing the central nuclei and outer electrons, the high speed electrons can also shoot through them without being stopped or deviated.

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[1] Thomson Research Laboratory, G. E. Co., Lynn, Mass.

*Presented at a meeting of the Lynn Section, A. I. E. E., Lynn, Mass., May 18, 1927.*

When the cathode is cold the voltages necessary to produce such electronic currents would be of the order of millions of volts and the obtained currents expressed in milliamperes. In other words, for most purposes a space not occupied by either solid or gas of sufficient density is an insulator. There will not be any change in conductivity if a gas in a perfectly neutral state be introduced between the electrodes. The distances between the gaseous molecules, even if their number is increased to several billion of billions per cubic centimeter, are relatively so great that there cannot be any exchange of electrons as in solid conductors between the atoms and the space remains non-conducting. This, however, will cease to be so if the molecules acquire electrical charges.

Under usual conditions gases are subjected to various ionizing radiations such as the radioactivity of the earth, ultra violet rays, and the electrons emission from the hot bodies and flames. In atmospheric air these factors determine a generation of two to three ions per second per cubic centimeter. However small the degree of ionization may be, the gas will always contain a few ions and free electrons. If an electron moving under the influence of applied difference of potentials with sufficient velocity encounters or passes very near one of the outer orbital electrons of an atom, the repulsive forces between them may be such as to detach the orbital electron from the atomic system, which then remains with a unit positive charge. The removed electron may either repeat the same process with the next molecule or attach itself to it, thereby communicating a negative charge. This removal or attachment of one extra electron to the neutral molecules is called ionization.

Electrons so produced and ionized atoms or molecules will also start moving in the direction of the electric force and if the potential gradient is sufficient, will acquire such velocity that their impact on neutral molecules will ionize these. This process of cumulative ionization in a very short time will produce a sufficient number of carriers to transmit from one electrode to another a considerable current. Under certain special conditions, the highly ionized gas column may acquire an electric conductivity comparable with that of a good solid conductor. It might seem strange that a gaseous column can be almost as good a conductor as a copper rod, yet if we remember that the conduction depends only on the number of suitable carriers and on the velocity with which they can move this apparent paradox disappears. Now to pass from conduction through ionized gas to arc conduction, we shall consider the effect of the temperature of the cathode. When the cathode is brought up by some means to a high temperature the electrons will be ejected from its surface into the gas in great numbers. These free electrons can be considered as ions and the gas containing such electrons as an ionized gas. The voltage necessary to move these free electrons towards the anode can be comparatively low. If the gas is at a very low pressure, the electrons will move in straight lines between the molecules. Only a very few of these electrons will be stopped or deflected by collision with molecules. In this case the current will be purely electronic. However, when the molecules are present in larger numbers the electrons (if moving with sufficient velocity) will ionize the gaseous molecules and the current will be carried by ionized molecules as well as by the electrons.

The method of producing the intense initial ionization in the case of an electric arc is by taking advantage of the above described property of certain materials to emit electrons at high temperatures. To draw the arc between the two electrodes, they are brought in contact and a current of sufficient magnitude is passed across the contact. The resistance of the contact, especially just before the moment of separation of the electrodes, is high enough to cause rapid heating of the tips of the electrodes to incandescence, with the result that numerous electrons are projected into the surrounding gas, so that at the moment of separation of the electrodes, the gas contains large numbers of free electrons which under the action of the established electrostatic field will move and impinge on the gaseous molecules.

Since the separation of the electrodes is done gradually, even with comparatively low voltages the potential gradient during the first moment will be sufficient to give the necessary acceleration to the free electrons which at the end of their free path will possess energy to ionize the gaseous molecules. The ionized molecules and electrons will move and impinge on the next neutral molecules but unless the potential gradient is sufficiently high, they will not acquire at the end of their free path a sufficient velocity and consequently will be unable to ionize the next set of molecules; therefore, the ionization will not continue. Since the distance between the electrodes continued to increase and the potential gradient to decrease, the current, after reaching certain magnitude, will fall to a lower value and finally stop altogether. But if the potential gradient during the separation of the electrodes be sufficient, the number of carriers will increase very rapidly until an appreciable current will flow between the electrodes which will produce rapid heating of gas. At higher temperatures the ionization occurs much more readily, so that as soon as the appreciable current flows, the ionization is more pronounced which again causes the current to increase. As soon as the cathode spot on the electrode is brought to a high temperature, a large volume of metallic vapor is sent into the stream which is easily ionized and will conduct practically the whole current. This is the arc conduction.

Since the drawing of the arc is done at a low temperature and the maintaining of the arc at high temperatures, the voltages necessary to strike the arc are always much higher than those used to maintain the arc.

This feature is taken advantage of in the design of a number of commercial welding generators which produce a high voltage only on open circuit. As soon as the arc is drawn, the voltage across the brushes automatically falls to a value only slightly higher than that of the voltage across the arc.

Since high temperature is essential to maintain easy ionization, any factor tending to cool off the electrodes or the arc stream will influence greatly the stability of the arc. If the temperature of the arc falls, the ionization of the materials in the arc stream does not take place as readily, so that the agent producing ionization must be more active. In other words, the speed with which the electrons and ions impinge on the neutral molecules must be higher which necessitates a high potential gradient; that is, higher arc voltage. One of the most powerful methods of cooling the arc core is by surrounding it with hydrogen, which at high temperature dissociates into the atomic state and absorbs large amounts of energy.

### ATOMIC HYDROGEN PROCESS

This phenomenon of dissociation of molecular hydrogen at high temperatures into the atomic state was discovered by Dr. I. Langmuir[2] during his studies of the laws of heat losses from a heated tungsten filament in hydrogen at low pressures. Dr. Langmuir observed that above certain temperatures, the heat losses instead of being proportional to 1.9th power of the absolute temperature, are proportional to a much higher power which increases with temperature.

The following studies of this phenomena established that these abnormally high losses are due to the dissociation of molecular hydrogen into the atomic state. Step by step Dr. Langmuir discovered the temperatures of dissociation, degree of concentration of the produced atomic hydrogen, the energy absorbed by the dissociation, the chemical properties of the atomic hydrogen and the thermic effects produced by recombination of the atoms into molecules.

The atomic hydrogen possesses many remarkable properties which have been studied in the last few years by several investigators. Many chemical reactions impossible with molecular hydrogen take place when that gas is in the atomic state. The most stable oxides can be reduced into the metallic state. Substances which are usually considered as the most refractory materials can be melted by the flames of atomic hydrogen. And certain hydrogen compounds which formerly could be produced in very small concentrations, now may be obtained in 100 per cent concentrations. There are two methods of producing atomic hydrogen.

One discovered by Dr. Langmuir is by increasing the speed of the thermal agitation of hydrogen molecules until the forces between the two atoms composing the molecule are not sufficient to hold them together. They spring apart and by doing so absorb large amounts of energy from the source producing that thermal agitation. In this method all molecules subjected to the high temperature are being acted upon simultaneously. This is (if we can use such a term here) a "mass production."

The other way of disrupting the hydrogen molecule is by hitting it with a heavy atom, moving with high velocity. In this method the hydrogen molecules are dissociated one by one and only when shot with a swiftly moving atom. Using again a shop term, we can call it "piece work." However, Dr. Langmuir developed the first method which permits the production of atomic hydrogen in high concentration, which permits the use of atomic hydrogen not only as a special chemical regent but also as one of the most remarkable agents for transmission of thermal energy. To accomplish this, it was necessary to produce the atomic hydrogen not inside of a vacuum container, but in the open air. The method adopted by Dr. Langmuir consists in blowing a stream of molecular hydrogen through an electric arc maintained between two tungsten electrodes.

The temperature of the arc core is sufficient to produce complete dissociation of the whole mass of the gaseous layer in contact with it. The produced atomic hydrogen diffuses rapidly away from the arc core and recombines in the cooler regions into the molecular state, forming an extremely hot flame of a single gas which burns without oxygen. The evolved heat, of course, is the energy previously absorbed from the arc. It was found that the heat of formation of molecular hydrogen is equal to 98,000 calories. In other words, when the atomic hydrogen recombines to produce one cubic foot of molecular hydrogen (measured at N. T. P.), the amount of heat produced is 455 B. t. u This quantity is greater than that obtained by the combustion of one cubic foot of molecular hydrogen in oxygen. In the last case the amount of evolved heat will be only 316 B. t. u.

The greatest advantage of the atomic hydrogen resides not in the amount of energy transmitted but in the high potential at which that energy is delivered. In other words, the remarkable property of the atomic hydrogen is the temperature of its flame. Dr. Langmuir's calculations show that this temperature is at least 3717 deg. cent. One of the experimental confirmations of these conclusions is the fact that tungsten, the metal with the highest known melting point, can be melted in the atomic hydrogen flame but not in any other flame.

The importance of the temperature of the flame can be illustrated by the comparison of two combustible gases; one of which is acetylene and another is propane. The amount of energy produced by combustion of one cubic foot of acetylene is 1456 B. t. u. The corresponding value for propane is 2465 B. t. u.

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[2] Flames of Atomic Hydrogen, *General Electric Review*, March, 1926.

In spite of much lower heat capacity of acetylene, the temperature of its flame (about 3000 deg. cent.) is higher than that of propane (about 2100 deg. cent.) and the result of it is that the welding with that gas is much faster than with the latter.

One of the practical applications of the atomic hydrogen flame is for welding of metals. In this field it has received lately numerous applications on account of its two properties especially valuable for welding work; namely, the extremely high temperature of the flame and the reducing properties of the gas forming that flame.

As a welding tool the atomic hydrogen torch must be compared with the oxyacetylene torch. It has similar characteristics in that the most of the energy is produced in a comparatively small inner cone or fan where extremely high temperature is attained. This inner hot zone is surrounded by the flame of reducing gas with temperatures gradually falling to that of the outer mantle of the flame where the recombined molecular hydrogen is burning in contact with the air. The temperature of that part of the flame is something like 1000 deg. cent.

This gradual change of temperatures gives an extreme flexibility to the atomic hydrogen torch. It insures a perfect control of speed of welding and of the temperature of the molten metal in the weld. This last factor is of a paramount importance for welding in hydrogen atmosphere. This gas is only slightly soluble in molten iron just above the melting point. But with a rise of temperature its solubility increases very rapidly. When the molten iron is overheated, it will absorb at least 15 times its own volume of gas (measured at N. T. P.). During the solidification most of that gas will be precipitated out and unless special precautions are taken, will form numerous blow holes.

However, if the welder follows the right technic by forming only a shallow pool of molten metal which insures a low temperature of the molten iron, hydrogen will be prevented from going into solution and the resulting weld will be perfectly free from gas pockets.

The atomic hydrogen torch embodies in itself all the necessary conditions not only to transmit from the arc into the plate any desired amount of energy, but also to do it at a very high speed. The high speed of recombination of the atomic hydrogen into the molecular state is determined by the steep gradient of temperatures and also by the catalytic action of the metal in the weld.

This recombination of the atomic hydrogen at the surface of the liquid metal in the weld to a certain extent replaces the oxidation reaction always present when the welding is done in air. This reaction supplies the necessary auxiliary heat to keep the surface of the solidifying metal in the molten state long enough to permit the absorbed gases to escape freely.

The a-c. arcs used in the atomic hydrogen process are usually two or three cm. in length bent in a shape of a fan between two tungsten electrodes placed to form a "V". The voltage drops at the surface of the electrodes, which correspond to anode and cathode drops in d-c. arcs, are equal to about 18 volts each. With the usual arcs of about 100 volts, the 36-volt drop at the surface of the electrodes, therefore, represents one-third of the total arc voltage, so that two-thirds of the energy absorbed in the dissociation of hydrogen into atomic state comes from the long arc core. The usual arc voltage is about 100 volts and the open circuit voltage of the welding circuit is seldom less than three or four times that value. The energy absorbed by the weld, of course, is that which comes from the arc; the atomic hydrogen plays the role only of an exceptionally efficient transmitter.

The energy evolved by burning the molecular hydrogen in contact with the air, serves only to raise slightly the temperature of the plate outside the weld but does not affect appreciably the weld itself. Most of that energy is radiated into surrounding space.

### THE SHIELDED ARC PROCESS

While the work on atomic hydrogen was proceeding in the Schenectady Laboratory, the writer was engaged in the Lynn Laboratory on the development of an improved method of the arc welding with metallic and carbon electrodes.

Since the accepted explanation of brittleness in arc welds was the presence in the weld of oxides and nitrides of iron, the first experiments were conducted on welding in gases other than those composing the atmospheric air. The first experiments were conducted on welding in carbon dioxide, superheated steam, and illuminating gas. Then, without any knowledge of Dr. Langmuir's experiments with atomic hydrogen, the writer came to the conclusion that it is hydrogen which must give the desired results. The experiments immediately confirmed this view. The welds produced in that gas proved to be perfectly ductile and to possess a high tensile strength. Furthermore, it was found that the apparent resistance of the welding arc in hydrogen is more than twice that of the same arc in air. Because of the desirability of rapid deposition of the metal, the welding arc must have a definite short length. The increase of the apparent resistance of the arc without increase in length is most welcome as it makes the arc almost twice as efficient as a device for the transformation of the electrical energy into the thermal form.

The anode and cathode voltage drops of an iron welding arc of 100 amperes maintained in hydrogen atmosphere were found to be each equal to 16 volts. The voltage drop across the arc stream for an arc of ⅛ inch does not exceed 5 volts, so that the total voltage across the arc of ⅛ inch in length is 37 volts. The usual arc voltage of the welding arcs of the same length and current intensity maintained in air is about 18 volts.

This abnormal apparent resistance of the arc in hydrogen, the writer at that time attributed to an xeceptionally high coefficient of heat conductivity of that gas. Indeed the heat conductivity of air is $0.5 \times 10^{-5}$ and that of hydrogen is $3.17 \times 10^{-5}$ calories per cm. per sec. per deg. cent. In other words, it was thought that the high voltage of the arc is due to a mere cooling of the arc by hydrogen in its molecular form.

At a later date, to check up this assumption, the writer repeated the same experiments with the arcs in helium. This gas has also an exceptionally high coefficient of heat conductivity which is even slightly higher than that of hydrogen; namely, $3.39 \times 10^{-5}$. The experiments, however, showed that the arc voltage in that gas is lower even than in air. Since the coefficients of diffusion of hydrogen and helium are about the same and the temperature of the arc core in both cases probably does not differ materially, the only explanation of difference in the arc voltages was that the hydrogen, being a diatomic gas, was dissociated into the atomic state while the helium, being a monatomic gas, remained unchanged by the extreme temperature of the arc.

These experiments have an interest only as illustration of various ways of investigation. The quantative determination of the amount of atomic hydrogen produced cannot be based on such experiments. They only demonstrate the fact of the dissociation of hydrogen into the atomic state and that it affects very markedly the anode and cathode fall.

These two quantities are determined by the concentration of the ions of one sign at the surface of the electrodes. If the production of the ions of the other sign in the first gaseous layers next to the electrode is slowed down, the electrostatic charges of the incoming ions will determine a very steep potential gradient. The dissociation of hydrogen into the atomic state cools off the surface of the anode and cathode and, therefore, reduces there, the speed of ionization and emission of thermions. The role of atomic hydrogen in the shielded arc process can be compared with the most effective means of cooling the electrodes.

Of course, the atomic hydrogen produced undoubtedly affects also the quality of the weld, making it more free from oxides. This last action, however, is not as important as that which increased the efficiency of the arc, since in the shielded arc process, the weld is fully protected by a large volume of the molecular hydrogen which at the high temperature of the arc is also one of the most energetic reducing agents.

## THE DEPOSITION OF METAL

The transfer of the metal from the electrode to the plate can be either purely ionic or mechanical. In the first case the metal is rapidly vaporized from the electrode, enters the arc and after being ionized is moved across the arc to the surface of the positive crater where it regains its state of neutral atoms and condenses as a vapor on the surface of the crater. The speed of motion of gaseous ions is very high so that large quantities of metal can be transferred from the electrode to the weld in a very short time. The hypothesis of transfer of the metal in the state of vapor has been advanced by Professor Slocum.[3] This type of metal transfer is observed only with long arcs.

The writer's experiments indicated that the temperature of the anode is the determining factor in the ionic transfer of the metal in the welding arc. If an arc of 125 amperes and 60 volts be maintained in hydrogen between a cold plate and ⅛-in. Armco pure iron electrode, the transfer of metal will be mostly mechanical. The tip of the electrode will be liquified and the large drops of metal will be periodically falling down on the plate. The vapor stream from the negative electrode will enter the arc, but there will not be appreciable condensation of that vapor on the plate If, however, the positive crater be allowed to establish itself on the plate and the temperature of the molten metal in the crater rises above a certain limit, then the arc will become very stable and practically the total amount of metal will pass through the arc in a state of ionized vapor. The speed of "vapor deposition" of metal is about the same as that which would be with the short arcs of the same current density when practically the total amount of metal is passing through the arc in the liquid state. However, in usual practise, the arc length is so short that the intense radiations from the positive crater affect not only the surface of the negative crater but also the whole tip of the electrode to a considerable length. This results in rapid melting of the tip of the electrode which is in more or less plastic state to a distance of three or four millimeters from the negative crater. This condition determines an entirely different mode of transfer of metal across the arc. The wire used as electrodes always contains a large amount of occluded gases. The actual volume of occluded gases depends on the method of manufacturing of the wire and in certain instances may reach many times the volume of the metal.

The amount of gas which the metal can hold in the occluded state depends on the temperature. At the temperature of red heat, most of the gases are expelled from the metal. Since the tip of the electrode is in molten state, it is mechanically the weakest point and the gases escape in that direction which results in periodical rupture of the liquid surface of the tip of the electrode and projection of it into the direction of the positive crater. If the arc is very short, this ruptured part of the tip of the electrode short-circuits the arc. In other words, it bridges the tip of the electrode with the positive crater. As soon as the globule touches the liquid surface, another set of forces comes into play; namely, the surface tension of the molten metal. Now the globule is pulled towards the liquid by the surface

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3. The Welding Arc. *Welding Engineer*, January, 1921.

tension and so breaks the contact with the electrode. If the time of transfer was short, the temperature of the ionized gases was not affected appreciably so that the arc can be readily restarted. The experimental proof of this mechanism of transfer of molten metal across the welding arc was furnished by many investigators amongst whom we must name Professor Hudson[4] who advocates the theory of liquid transfer of metal determined by the expulsion of the gases, and Mr. O. H. Eschholz[5] who demonstrated that even without the explosive action of gases, the metal can be transferred through the action of the forces of the surface tension. However, the writer is of the opinion that both types of forces are responsible for the transfer of the metal in the short welding arc.

## PHYSICS AND CHEMISTRY OF THE CRATER

In the case of arc welding with a metallic electrode, the positive crater is established on the plate itself. This is the most efficient method of transmitting the energy of the arc into the plate. In this case not only the metal is subjected to the radiations from the negative crater and the arc core, but it is also the subject of the most terrible bombardment by the electrons and ions rapidly moving towards the anode. The velocity of gaseous ions in the arc core is not definitely known but it may be expected to be very high. Furthermore, the condensation of the gaseous ions on the liquid surface of the crater is accompanied by the evolution of the latent heat of evaporation of electrons and gaseous atoms. This last factor explains the difference in the calorific effects at the anode and cathode of the arc in spite of the fact that the anode and cathode potential drops, as in the case of the iron arc in hydrogen, are the same. The surface of the metal is heated so rapidly that the heat has no time to be conducted away through the thickness of the metal. Therefore, the metal around the foot of the arc core is liquefied and forms a shallow molten pool. The metal in this molten pool is a subject of several actions. First, the rapidly falling metallic globules splash the molten metal so that the surface of the crater is continually swept by the waves running from the center of the crater to the periphery. Secondly, the molten metal, being free to move, is repulsed from the foot of the arc by the electromagnetic interaction of the currents carried by those parts of the arc and moves towards the edges of the molten pool, forming a sort of a shallow cup or a crater.

The absorption and evolution of gases in different parts of the crater is a factor of paramount importance. The accurate tests conducted by Dr. Baraduc-Muller,[6] who was experimenting with the masses of molten steel weighing 11,000 pounds, demonstrated that molten steel may hold in solution very large amounts of gases. For instance, the volumes of hydrogen, carbon monoxide and nitrogen occluded in one cubic foot of molten Bessemer steel are respectively equal to thirteen, eight and five cubic feet (measured at N. T. P.).

The writer's experiments with hydrogen, helium, argon, carbon monoxide, and nitrogen occluded in the molten part of the crater gave about the same figures and indicated that these gases are precipitated out from the molten steel when it is still fluid. The observation of the large craters of the powerful arcs burning in different gases reveals that all these gases are absorbed in the hot part of the crater and evolved in a form of a stream bubbles coming to the surface of the molten metal in cooler parts of the crater.

This continual process of absorption and evolution of gases is equivalent to an energetic washing of the molten metal with hot gas. The occluded gases may react with the metal and form nitrides, oxides, hydrides or may simply be held in solution and be partly precipitated out during the solidification. At any rate the large amounts of absorbed and later evolved gases have a very great bearing on the soundness of the deposited metal and the number of blow holes which it may contain.

When the arc is maintained in air, the fundamental chemical reaction in the crater of the arc is oxidation. Oxygen of the air coming in contact with the molten metal reacts almost instantaneously and forms $FeO$ which is gradually dissolved in the mass of the metal. The excess of that oxide floats on the surface in a form of a slag and being further oxidized during the freezing of the metal to $Fe_3O_4$. The oxidation or burning of the surface layer of the molten metal in the arc crater has a determining influence on the number of gas inclusions in the weld metal. As has been demonstrated by the writer's experiments on welding arcs in argon-oxygen mixtures,[7] the amount of heat produced by the oxidation reaction is sufficient to maintain the surface of the freezing metal near the edge of the crater in molten state long enough to allow all the gases to escape freely and leave the weld metal free from blow holes.

When the deposition of the metal is done in reducing or neutral atmosphere, this reaction is suppressed and unless special precautions are taken, the weld metal will contain numerous blow holes.

It may be pointed out here that in the atomic hydrogen process, the recombination of the atomic hydrogen into the molecular form at the surface of the weld metal provides a source of large amount of energy. In this way the atomic hydrogen process not only suppresses the deleterious action of oxidation but also provides means to replace the important and desirable influence of that reaction by a new reaction which takes place of the old one. In the shielded arc process, other means are used to assure the prompt expulsion of the occluded gases.

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[4] A Theory of Metallic Arc Welding, *Journal of Am. Welding Society*, October, 1919.

[5] Metal Deposition in Arc Welding, *Electrical World*, June, 1920.

[6] The Gases Occluded in Liquid Steel, *Iron and Steel Institute Carnegie Scholarship*, Memoir, 1909.

[7] Oxidation of the Arc Crater, *Journal of Am. Welding Society*, December, 1926.

### WELDING IN MIXED GASES

The development of the shielded arc process extended also to the making of welds in mixtures of hydrogen and carbon monoxide according to the ideas of Prof. E. Thomson.

The tests demonstrated that the metal deposited in that atmosphere possessed about the same ductility as those produced in pure hydrogen. Furthermore, it was found that the arc in water gas is much more stable than in hydrogen and does not necessitate the open circuit voltage even for welding with comparatively low currents, higher than used for standard work of welding in air.

Other tests were made with various gaseous mixtures. In conjunction with Professor Thomson the author found that not only various mixtures of hydrogen and carbon monoxide could be used for welding work, but that certain organic liquids such as methanol and denatured ethyl alcohol when vaporized will serve the same purpose as the pure hydrogen.

Working in conjunction with Dr. Langmuir, the author also carried out a series of tests which demonstrated that for certain purposes nitrogen mixed with certain amounts of hydrogen gives welds of superior quality. It should be mentioned here also that the mixture of hydrogen with argon was suggested to the writer by Mr. P. K. Devers.

The work conducted on welding in various gases resulted in the development of practical means of producing these gases easily and at a low cost from various organic and inorganic compounds such as alcohols, ammonia, propane, etc. Since these compounds are liquids or liquefied gases, the question of storage and transportation has also been solved. This can be made clear if we consider that one gallon of methanol will give on vaporization and dissociation in the arc over 240 cubic ft. of gas. The development of welding in alcohol vapors should be especially emphasized as one of the most practical solutions found in this laboratory of the problem of storage and cost of the most suitable gas for welding by the shielded arc process which is water gas.

When instead of pure hydrogen, the shielding gaseous atmosphere is provided by the gaseous mixture of carbon dioxide with propane or the vapors of alcohol, the function of the arc is not only to liberate sufficient amount of energy to melt the metal but also by dissociating the gaseous raw materials, produces a suitable mixture of hydrogen with carbon monoxide. The electric arc here becomes not merely a source of heat but also a chemical laboratory.

If we try to visualize all that is happening in the small space occupied by the arc, all the different chemical reactions, transformation of electrical energy into thermal form, absorption and evolution of gases and the deposition of metal, one begins to wonder how it is possible for the welder to take care of all these complicated factors. The answer is that they take care of themselves. If the conditions are regulated rightly, all these processes are entirely automatic and the man has to watch only the needle of the meter.

After going through this description of the atomic hydrogen and the shielded arc processes, one may ask, "What is the purpose of this development? What is all this for? Is it easier to use a combination of the electric arc with the gas instead of using each of these factors singly?"

The answer to the last question is "no." Of course, the combination of several factors necessitates better technique and more accurate adjustment of all the conditions. But what is complicated today will be a simple thing tomorrow.

It is simpler to make a lamp with the tungsten filament in the vacuum than a combination of the same filament and the gas. But who wants now the older and simpler type of the incandescent lamp? The present arc welding processes are all right and give excellent results in every field of their applications. But so did the rivet thirty years ago.

There was a time when no one dreamed of using anything but pure wrought iron. Then there came an age of iron-carbon alloys; that is, of steel. And now we are entering the era of alloy steels. Most of those steels contain such easily oxidizable elements as chromium. And unless the weld is protected by a reducing atmosphere, the results on welding such materials are not satisfactory. It is in this field that the new processes probably will find their best applications.

The electric arc and the gas flame will, in the future, replace rivet cutting tools and the foundry mold. Amongst innumerable fields of applications, there will be demand for every kind of welding and cutting processes. The described processes will not replace any of the existing processes but simply assume their place of usefulness amongst the older brothers and do the job which cannot be done without their help.

# Computation of the Unbalance Factor

## of a Three-Phase Triangle When Lengths of Three Sides are Given

BY A. E. KENNELLY

In an important paper read before the June 1918 Convention of the A. I. E. E., it was shown by Mr. C. L. Fortescue that any dissymmetrical system of three-phase voltages or currents could be resolved, by vector methods, into a pair of symmetrical systems, one forward and the other backward. The numerical ratio of the latter to the former is called the unbalance factor of the system. Although several vector methods were developed in the paper and its discussion, for evaluating the forward and backward components when the dissymmetrical triangle is given, so far as is known to the writer, no scalar and purely numerical method of developing them has been published. As it is useful sometimes to compute the two components without recourse to vector methods or to the drawing board, a numerical method is here offered.

Let $A\,B\,C$, Fig. 1, be the dissymmetrical three-phase triangle, say of voltages $A\,B = 1100$, $B\,C = 1000$, and $C\,A = 900$, the system having counterclockwise rotation. One of the now well-known vector methods for deriving the forward and backward components is shown. With center $A$ and radius $A\,C$, arcs of 120 deg. and 240 deg. are drawn counterclockwise to the points $d_1$ and $e_1$, respectively. Again, with center $B$ and radius $B\,C$, arcs of 120 deg. and 240 deg. are drawn clockwise to the points $D$ and $E$ respectively. Lines $d_1\,D$, and $e_1\,E$, are then drawn as shown. Each of these lines is trisected, as at $d_1\,d_2$ and $e_1\,e_2$. Equilateral triangles $d_1\,d_2\,d_3$ and $e_1\,e_2\,e_3$ are then constructed on these segments. These are known to be the equivalent symmetrical component systems. The equilateral triangle $d_1\,d_2\,d_3$ is drawn with forward rotation or counterclockwise, like $A\,B\,C$, and the equilateral triangle $e_1\,e_2\,e_3$ with reverse or backward rotation.

The vector sum of $d_1\,d_2$ and $e_1\,e_2$ is then equal to the vector $A\,B$,

The vector sum of $d_2\,d_3$ and $e_2\,e_3$ is then equal to the vector $B\,C$,

The vector sum of $d_3\,d_1$ and $e_3\,e_1$ is then equal to the vector $C\,A$.

In this case, the sides of the forward or $d$ triangle measure 996.6 volts, and the sides of the backward or $e$ triangle measure 115.9 volts. The unbalance factor of the $A\,B\,C$ triangle or system is then $115.9/996.6 = 0.116$.

An equivalent numerical method is as follows:

Let $A_m$ be the r. m. s. of the sides of the given triangle $A\,B\,C$, and let $A_s$ be the side length of an equilateral triangle having the same area as the actual triangle $A\,B\,C$; then the side squares $d^2$ and $e^2$ of the forward and backward components will be respectively the half sum and the half difference of $A_m^2$ and $A_s^2$. Thus

$$d^2 = \frac{A_m^2 + A_s^2}{2} \qquad (1)$$

and

$$e^2 = \frac{A_m^2 - A_s^2}{2} \qquad (2)$$

The unbalance factor is then, as before, $e/d$.

Let $a$, $b$, and $c$, be the three known sides of the dissymmetrical system triangle $A\,B\,C$. Then the mean square of these sides is:

$$A_m^2 = \frac{a^2 + b^2 + c^2}{3} \qquad (3)$$

Again, if the half-perimeter $p$ of the triangle $A\,B\,C$ is

$$p = \frac{a + b + c}{2} \qquad (4)$$

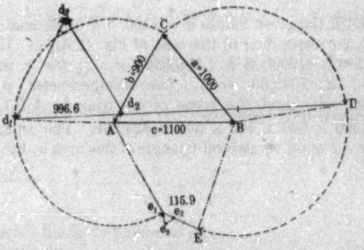

FIG. 1—DIAGRAM SHOWING ANALYSIS OF A DYSSYMMETRICAL SYSTEM $A\,B\,C$, BY ONE OF THE USUAL VECTOR METHODS INTO FORWARD AND BACKWARD COMPONENTS

it is shown in text-books of plane trigonometry that the area of the triangle $A\,B\,C$ is:

$$s = \sqrt{p\,(p-a)\,.\,(p-b)\,.\,(p-c)} \qquad (5)$$

If $A_s$ is the length of the side of an equilateral triangle $A\,B\,C$, Fig. 2, the area $S$ of this triangle, being equal to half the product of the base $A_s$ and the height $h$, we have

$$h = A_s \cos 30° = A_s \sqrt{3}/2 \qquad (6)$$

so that

$$S = \frac{h\,.\,A_s}{2} = \frac{A_s^2\sqrt{3}}{4} \qquad (7)$$

or

$$A_s^2 = \frac{4\,S}{\sqrt{3}} \qquad (8)$$

If we take $S = s$, we have

$$A_s^2 = \frac{4\,s}{\sqrt{3}} \qquad (9)$$

and $A_s^2$ is now the side square of an equilateral triangle equal in area to $A\,B\,C$. Then

$$d^2 = \frac{A_m^2 + A_s^2}{2} = \frac{a^2 + b^2 + c^2}{6} + \frac{2\,s}{\sqrt{3}} \qquad (10)$$

and

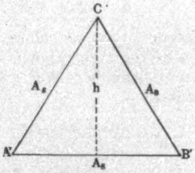

Fig. 2—Equilateral Triangle of Side $A_s$

$$e^2 = \frac{A_m^2 - A_s^2}{2} = \frac{a^2 + b^2 + c^2}{6} - \frac{2\,s}{\sqrt{3}} \qquad (11)$$

With the given values $a = 1100$, $b = 1000$, and $c = 900$, corresponding to the case of Fig. 1, $A_m^2 = (1100^2 + 1000^2 + 900^2)/3 = 1{,}006{,}666$, or $A_m$, the r. m. s. side, is 1002.66 volts. The semiperimeter $p$ is 1500 volts, and the areas of the triangle $A\,B\,C$ is $\sqrt{1500 \times 600 \times 400 \times 500} = 424{,}264$. The squared side $A_s^2$ of an equilateral triangle of this area is, by (**9**), $424{,}264 \times 4/\sqrt{3} = 979{,}796$. or $A_s = 989.846$. We then have, by (**1**),

$$d^2 = \frac{1{,}006{,}666 + 979{,}796}{2} = 993{,}231, \text{ and } d = 996.61$$

volts; while

$$e^2 = \frac{1{,}006{,}666 - 979.796}{2} = 13{,}435, \text{ and } e = 115.91$$

volts.

The unbalance factor, as before, is 115.91/996.61 = 0.1163.

In the extreme case of a symmetrical three-phase system, represented by an equilateral triangle, $a = b = c = q$ say, and the r. m. s. side $A_m$ is also $q$. Moreover the side $A_s$ of the equilateral triangle of equal area is evidently also $q$. In that case, $d = \sqrt{\dfrac{q^2 + q^2}{2}} = q$,

and $e = \sqrt{\dfrac{q^2 - q^2}{2}} = 0$; so that the unbalance factor vanishes.

In the opposite extreme case of a flat three-phase system, reduced to the single-phase type; so that $A\,B$, $B\,C$, and $C\,A$ are all in the same straight line, the area of the system triangle vanishes, and so does the side length $A_s$. Consequently, $d = \dfrac{A_m}{\sqrt{2}} = e$, and $e/d$, the unbalance factor, becomes unity.

# A Note on the Unbalancing Factor of Three-Phase Systems

BY A. PEN-TUNG SAH
Material & Process Engg. Dept. Westinghouse Elec. & Mfg. Co.

In an article appearing in the A. I. E. E. JOURNAL for March 1927, Prof. A. E. Kennelly gave the following analytic expressions for computing the forward (positive-phase or direct sequence) and backward (negative-phase or reverse sequence) components of a dissymmetric three-phase vector triangle.

$$\text{(A)} \qquad d^2 = \frac{a^2 + b^2 + c^2}{6} + \frac{2\,s}{\sqrt{3}};$$

$$e^2 = \frac{a^2 + b^2 + c^2}{6} - \frac{2\,s}{\sqrt{3}};$$

in which $a$, $b$, and $c$ are the lengths of the vectors forming the triangle and $s$ its area; $d$ and $e$ being the magnitudes of the forward and backward components respectively. In deriving expressions (A), he started from the relations—

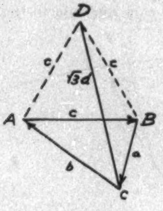

FIG. 1

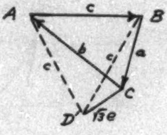

FIG. 2

$$\text{(B)} \qquad d^2 = \frac{A_m^2 + A_s^2}{2}; \quad e^2 = \frac{A_m^2 - A_s^2}{2}$$

where $A_m$ is the r. m. s. of the sides of the given triangle $A\,B\,C$ and $A_s$ the side length of an equilateral triangle having the same area. Judging from the fact that Professor Kennelly did not state how (B) could be derived, this must be either self-evident or very simply derivable from his geometrical construction of the forward and backward components. However, the present writer has failed to see this and it will be shown in the following that the relations (A) can be very simply obtained from an alternative method of geometrical construction of the components.

It is well known that the following constructions for the components hold:

Let $A\,B\,C$ be the given vector triangle. Construct an equilateral triangle $A\,B\,D$ externally on the side $A\,B$ as in Fig. 1. Then the magnitude of the forward component is given by $C\,D/\sqrt{3}$. If we construct the triangle $A\,B\,D'$ internally as in Fig. 2, we get $C\,D'/\sqrt{3}$ as the magnitude of the backward component. The lengths $C\,D$ and $C\,D'$ are readily computed. From Fig. 1 by the law of cosines, we have—

$$3\,d^2 = \overline{C\,D}^2 = b^2 + c^2 - 2\,b\,c\cos\,(60° + \angle\,B\,A\,C)$$

$$= b^2 + c^2 - 2\,b\,c\left[\frac{1}{2}\cos\,\angle\,B\,A\,C - \frac{\sqrt{3}}{2}\sin\,\angle\,B\,A\,C\right]$$

As $\frac{1}{2}\,b\,c\sin\,\angle\,B\,A\,C =$ Area of $\Delta\,B\,A\,C = s$ and

$$2\,b\,c\cos\,\angle\,B\,A\,C = b^2 + c^2 - a^2,$$

$$3\,d^2 = b^2 + c^2 - \frac{1}{2}\,(b^2 + c^2 - a^2) + 2\,\sqrt{3}\,s \text{ or}$$

$$d^2 = \frac{a^2 + b^2 + c^2}{6} + \frac{2\,s}{\sqrt{3}}$$

which is the first equation in (A).

Similarly,

$$3\,e^2 = \overline{C\,D'}^2 = b^2 + c^2 - 2\,b\,c\cos\,(60° - \angle\,B\,A\,C)$$

$$= b^2 + c^2 - 2\,b\,c\left[\frac{1}{2}\cos\,\angle\,BAC + \frac{\sqrt{3}}{2}\sin\,\angle\,BAC\right]$$

$$= b^2 + c^2 - \frac{1}{2}\,(b^2 + c^2 - a^2) - 2\,\sqrt{3}\,s$$

$$\text{i. e.,} \quad e^2 = \frac{a^2 + b^2 + c^2}{6} - \frac{2\,s}{\sqrt{3}},$$

which is the second one of the relations (A).

In passing it should be noted that the constructions herein given do not give the correct phase relation of the components. To get the correct phase relation the line $C\,D$ has to be rotated through an angle 30 deg. counter clockwise and $C\,D'$ through 30 deg. clockwise in order to get the respective positions of the forward and backward components. The unbalancing factor is by definition $e/d$.

# The Interpolar Fields of Saturated Magnetic Circuits

BY TH. LEHMANN[1]

Non-member

***Synopsis.****—In this note, the question of the effect of assuming infinite permeability in the iron on the accuracy of calculations of the interpolar fields in electric machines is studied.*

*One can do this very easily by replacing the saturated by non-saturated poles, covered by an infinitely thin sheet of current giving the same tangential component of the field along the surface of the iron. The field produced by this sheet of current, then, represents the difference between the exterior fields of the saturated circuit and of the non-saturated circuit.*

*In addition to this indirect method of estimating the influence of saturation, the sketch of the field between the poles and in the air-gap can also be directly developed by determining with the aid of the differential field, the point of indifference of the saturated circuit. A comparison of sketches obtained in this way shows that, for the same useful flux, the interpolar fields are almost the same in both cases. From these sketches and others which will appear shortly in the Revue Générale de l'Electricite, it is evident that the sketches and functional curves given by Messrs. Stevenson and Park, and Wieseman, in their very valuable work, can still be used even though the poles are saturated.*

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### INTRODUCTION

SUPPLEMENTING my discussion of the very interesting papers presented by Messrs. Stevenson and Park, and Wieseman, at the last Mid-Winter Convention of the A. I. E. E., I should like to show briefly how, from the sketches of lines of force given by these authors, the distribution of the interpolar field can be obtained when the poles or the teeth are saturated.

I have chosen for this the magnetic circuit of a d-c. dynamo which has open armature slots. First, by assuming that the iron has infinite permeability, the sketch in Fig. 1 is obtained with four lines of no work, or gradients, which outside of the coil become lines of equipotential. This process of development is well known. In this case, the area of the coil has first been subdivided into four equal parts, and the last one of these, at the top, into eighths and sixteenths, etc., which makes it possible to see at a glance that each gradient[2] encloses that fraction of the total area which corresponds to its order. This is not sufficient, however, to obtain the exact position of the point of indifference[3] toward which the gradients converge and where the field is zero. It is necessary to make sure at the same time that the reluctances $R_1, R_2, R_3 \ldots$ of the parts of the same tube from one pole to the other are proportional to the ampere-turns $I\,n_1, I\,n_2, I\,n_3 \ldots$ enclosed by the gradients which cut off these portions of the tubes; otherwise the distance of the point of indifference from the side of the coil might vary from 1 to 2.

It is therefore necessary to check the relations $R_1 : R_2 = I\,n_1 : I\,n_2$, etc., as has already been shown under a different title in the *Revue Générale de l'Électricite* of September 22, 1923, p. 397.

When a portion of the tube is situated completely within the current-carrying region, the ampere-turns $I\,n_1$ included between the gradients which cut off that portion, are counted from the point of indifference to the line of force which forms the median of the portion of the tube under consideration. But if the portion of the tube falls partly in the interior and partly outside of the current-carrying region, it is preferable to count the ampere-turns $I\,n_1$ from the point of indifference to the first boundary line of the tube and add to that value half ampere-turns contained in the portion of the tube itself.

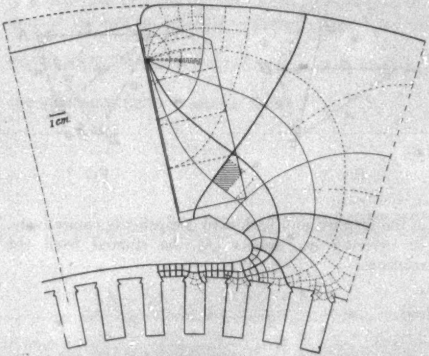

FIG. 1—SKETCH OF INTERPOLAR FIELD OF NON-SATURATED D-C. DYNAMO

Whenever the conductors in the portion of the tube form a rectangular section abutting against the two limiting lines of force, this reduction is applied, no matter what the thickness of the section, in the direction of the lines of force.

But when the current-carrying section does not cover the whole width of the tube from one line of force to the other, but only a fraction $(n/m)$ of this width, it can be

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1. Consulting Engineer, Urmatt (bas-Rhin) France.
2. Called "lines of no work" by Stevenson and Park.
3. Called "kernel" by Stevenson and Park.

shown that it is necessary to deduct a fraction $(n/2\,m)$ of the ampere turns confined in the elementary tube. For example, one should deduct ⅜ of the current-carrying section that covers transversely only ¾ of the width of the tube, regardless of the length of the section.

Finally, in the case where the contour of the coil cuts the tube obliquely, we can employ this same method by using judgment in replacing the oblique current-carrying zone of the tube by a rectangle of the same area, but of proportions so as to overlap the non-current-carrying zone as little as possible.

The magnetic field outside the field coil is Laplacian, and can be determined by subdivision into tubes of unit reluctance (curvilinear square tubes), according to the usual method. The sketch is commenced by full lines which are subdivided only in the regions where estimation of the elementary tubes would not be sufficiently accurate otherwise. I am inclined to think that it is not advisable to commence the sketch with too fine a subdivision, which uselessly increases the necessary sketching and renders the localization of errors more difficult. The larger subdivision has also the advantage that, in rectifying the errors, account can more easily be taken of the effect of local retouching on the rest of the sketch which has already been traced.

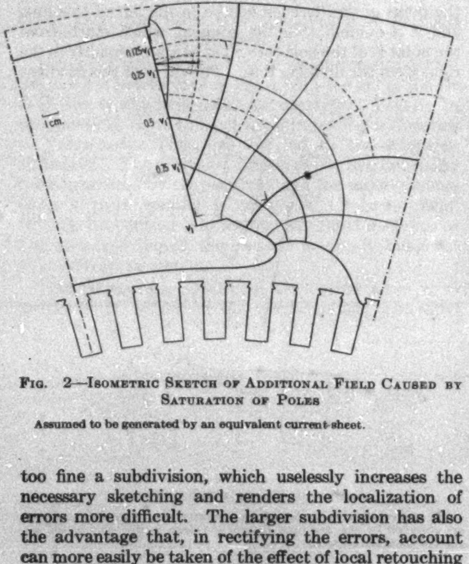

Fig. 2—Isometric Sketch of Additional Field Caused by Saturation of Poles

Assumed to be generated by an equivalent current-sheet.

## The Additional Interpolar Field Caused by the Saturation of the Poles

Fig. 1 represents a sketch obtained in this manner. Now, assume that the pole is saturated in such a manner that, for the same useful armature flux, the pole core absorbs one-third of the total field pole m. m. f. $4\,\pi\,i\,n$, so that the difference of potential caused by the saturation of the pole will be

$$v_1 = \frac{4\,\pi\,i\,n}{3}$$

where the current $i$ per turn is now in C. G. S. units. In Fig. 2, let us mark between the base and the top of the pole the points $0.125\,v_1$, $0.25\,v_1$, $0.5\,v_1$, and $0.75\,v_1$, calculated with the aid of the lines of flux in Fig. 1, and retouched as follows wherever necessary.

It has been shown in Sections III and IV of the mentioned article, that the field outside the iron will remain unchanged if the saturated core is replaced by a non-saturated core covered with an infinitely thin sheet of current. The current $j$ per unit length must satisfy the relation:

$$4\,\pi\,j = \frac{\partial v}{\partial x}$$

in such a way that at the height $x$ of the pole measured from its base, one will have:

$$v_x = 4\,\pi \int_0^x j\,d\,x$$

where $v_x$ designates the superficial potential at this point caused by saturation. This equivalence, it is well understood, cannot be extended to the field in the interior of the iron, in which we are not interested here.

On account of this, the problem can be considered as follows. We can consider the interpolar field as resulting from the superposition of fields generated by the actual current in the field pole coil and by the counter-magnetomotive force of a sheet of current corresponding to the actual saturation, assuming in both cases that the iron is infinitely permeable. It is sufficient, therefore, to superpose on the sketch of Fig. 1, which was obtained for $\mu = \infty$ in the iron using the field current which would be required for the saturated pole, another field produced by the sheet of current, also calculated for $\mu = \infty$ in the iron. The sum of these two fields will give us the actual resulting field in the interpolar space and in the air-gap when the core of the field pole is saturated. If the field spider or yoke is also saturated, the sheet of current would naturally be prolonged along its surface.

The sketch corresponding to the sheet of current is very easy to secure because it is entirely Laplacian and the starting points of the equipotential planes $0.75\,v_1$, $0.5\,v_1$ . . . are known in advance, and in addition, the lines of force in the air-gap near the neutral zone differ only slightly from those of Fig. 1. Generally, such a sketch requires only a few minutes.

But this is not all. We gain, at the same time, a method of predetermining the kernel, or point of indifference, when the pole is saturated.

## UTILIZATION OF THE DIFFERENCE FIELD FOR THE PREDETERMINATION OF THE POINT OF INDIFFERENCE

Since only equal and opposite fields annul each other, it is only necessary to search for the neighborhood where the gradients have the same direction and where the fields in Figs. 1 and 2 have the same intensity. Since the point of indifference must be in the interior of the coil, we notice immediately, when superposing Figs. 1 and 2, for example, against a window pane, that the gradients of Fig. 1 are tangent to the potential lines in Fig. 2 in the narrow slice which has been cross-sectioned vertically; see Fig. 1. The tangency continues far enough so that it is well to mark off a slice by the two gradients of Fig. 1, which coincide with only slight deviation with the potential lines of Fig. 2. It is only necessary now to compare the intensities of the fields. In Fig. 2, we see that the potential line on which the new point of indifference should be found is located in the square, the bases of which have a difference of potential $v_1/8$, and the lines of force a length of 1.95 cm. Assuming that the current density $i_0$ is $1/4\,\pi$ C. G. S. units the magnetomotive force of the whole field coil will be, for the scale of Fig. 1, 51 C. G. S. units, and that of the fictitious sheet of current 51/3 C. G. S. units, so that in the square tube under consideration in Fig. 2, the field $H$ expressed in C. G. S. units is:

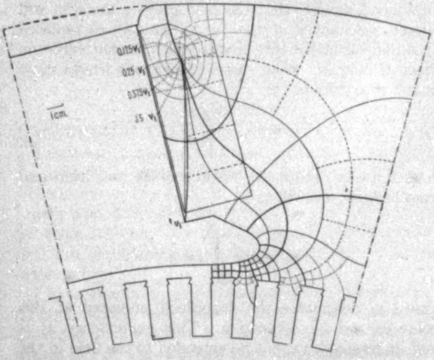

FIG. 3—SKETCH OF INTERPOLAR FIELD OF DYNAMO SHOWN IN FIG. 1, WHEN POLE IS SATURATED

The point of indifference has been moved toward the interior of the field coil. The ampere-turns on the left of the gradients issuing from the points $v_1$, are consumed in the pole; and those to the right of these gradients are absorbed by the air-gap.

$$H = \frac{51}{3} \cdot \frac{1}{8} \cdot \frac{1}{1.95} = 1.10 \text{ C. G. S. units}$$

If one compares in Fig. 1 the curvilinear sector formed by the gradients, which embrace the fourth and the eighth part of the section of the coil, to a circular sector, the radius of such a circular sector must be, according to a well-known relation, $r = \dfrac{2\,H}{4\,\pi\,i_0}$, and remembering that $i_0 = \dfrac{1}{4\,\pi}$ C. G. S. units is the assumed current density, we then have:

$$r = 2\ .\ 1.10 = 2.20 \text{ cm.}$$

and since the center of the equivalent circular sector falls one mm. behind the point of indifference, of Fig. 1, the new point of indifference will be found 2.10 cm. distance from the old one on the curved line bisecting the small cross-sectioned slice of Fig. 1.

## DIRECT DEVELOPMENT OF THE INTERPOLAR SKETCH WHEN THE POLES ARE SATURATED

Since we now know the point of indifference when the pole is saturated, we can easily develop the sketch of the interpolar field shown in Fig. 3, by dividing the area of the coil in the ratio 1:3 by a line which starts from the lower left corner of the coil. In this particular case, the point of indifference will be to the left of this line, and it is evident that the gradient which starts from the point $v_1$ of the pole core must be a little further to the right than the dividing line. The curve of this gradient will be given to us by the condition that on both sides of it the tubes of the same parameter must join without discontinuity, which makes it necessary to move the horizontal dotted lines which divide the coil in aliquot fractions sideways from this gradient until the proper concordance is obtained. The gradients which start from the pole core are easy to trace, since they join the points $v_1$, 0.5 $v_1$, 0.25 $v_1$, and 0.125 $v_1$, with the point of indifference.

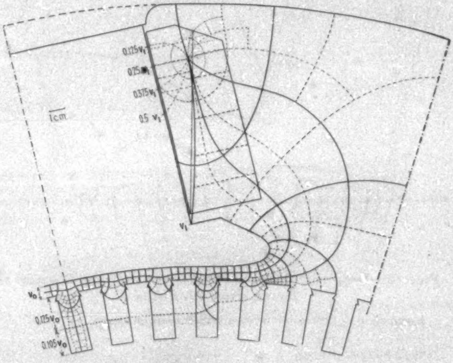

FIG. 4—LINES OF FORCE AND GRADIENTS WHEN POLES AND ARMATURE TEETH ARE SATURATED

The ampere-turns to the left of the gradients starting from the points $v_1$ are absorbed by the pole; and the ampere-turns to the right by the air-gap and the armature teeth.

Unfortunately, the same line of force was not taken as the starting point in Figs. 1 and 3, but one can, nevertheless, recognize that the total interpolar flux is slightly *weaker* for the saturated pole than for the non-saturated pole for the same useful flux (in spite of the fact that there were 50 per cent more ampere-turns in Fig. 3); but the difference is not more than 1 per cent of the useful flux.

### CASE WHERE POLES AND ARMATURE TEETH ARE SATURATED

In Fig. 4, the case has also been treated where the pole absorbs a third of the total ampere-turns, while the armature teeth consume 23 per cent of the ampere-turns consumed in the air-gap, as is indicated by the numbers 0.125 $v_0$ and 0.105 $v_0$, noted alongside the first tooth. The general appearance of the lines of force is, so to speak, the same as in Fig. 3, but the interpolar leakage flux is larger, since the ampere-turns necessary for the armature and the air-gap have become larger for the same useful flux.

### GENERALIZATION FROM THE SUPERPOSITION PROCESS OF SECTION II

Finally, it may be asked if one could not also obtain the point of indifference of Fig. 1 with the aid of the air field due to the field coils, for example? This is, in fact, possible, as we will soon show in the *Revue Générale de l'Électricite*. Thus, we are led to the following statement. The difference field between two interpolar fields generated by the same coil and the same currents along a given contour is always a Laplacian field, whether the contour is formed by saturated mediums or not, and even though the contour is simply imagined in an entirely air medium.

This principle is especially serviceable when it is necessary to determine the resulting field generated by several coils, as in the case of a d-c. dynamo having commutation poles, for example. The resulting fields in the slots when the teeth are highly saturated can be determined very well by this method. It is necessary to plate the walls of the teeth with sheets of current, giving the same tangential potential gradient along the teeth walls as the resultant field.

The principle of superposition of Section II can also be applied to space. It is sufficient to make 4 $\pi$ times the vector of the density $j$ of the superficial currents (in C. G. S. units) equal to the negative of the vectorial product of the normal exterior unit vector $n$ and the field vector $H$ at the exterior surface, as shown by the equation:

$$4\,\pi\, j = -\,[n, H]$$

### CONCLUSIONS

Summing up, it may be said that the interpolar sketches developed on the assumption that $\mu = \infty$ in the iron are generally sufficiently exact for all practical purposes, provided the interpolar flux is obtained from the number of field ampere-turns necessary for the air-gap and the armature.

When only the poles are saturated, the necessary correction is hardly ever more than 1 per cent of the useful flux, for the same potential difference between the pole tips.

But one can also develop directly the sketch in the air-gap, in the interpolar space, and in the slots, when the magnetic circuit is saturated. It is then advantageous to determine the additional Laplacian field caused by the saturation, which makes it possible to find the exact position of the points of indifference. As soon as these points are known, sketching the field presents practically no further difficulty.

The author wishes to express his gratitude to A. R. Stevenson, Jr., for translating this paper.

# Surge Impulse Breakdown of Air

BY J. J. TOROK*

Associate, A. I. E. E.

***Synopsis.**—This paper describes a phenomenon which is used as a method of studying the development of high-voltage sparkover. It has been found that if a voltage which rises very rapidly to a value more than sufficient to cause breakdown if continuously applied is impressed upon a sphere-gap, and this is very quickly reduced to a low value, luminous streamers are produced instead of the usual intense spark. These streamers can be observed with the eye and can be recorded on a photographic plate by the use of a quartz lens.*

*The phenomenon described and recorded is of intense interest because it presents the intermediate stages between the initiation of and the actual flashover between the spheres.*

*The effect on time lag of flashover with special reference to the state of ionization of the gas previous to flashover is also discussed.*

*Besides giving information on the mechanism of development of spark-over, this method of "suppressed discharge" has been used to determine the nature of the electrostatic field about insulators and between electrodes of various shapes.*

* * * * *

IN studying spark discharges, various investigators have tried to obtain the relation between voltages applied, lengths of gap, shape of electrodes, humidity, pressure, state of ionization, and various other factors in gaseous dielectric breakdown.

H. Hertz[1] discovered that the spark passed more easily when the electrodes were exposed to ultra violet light and later, E. Wiedemann and A. Ebert[2] proved that the spark was affected only when the light was projected on the cathode. G. Jaumann[3] concluded that the sparking voltage was determined also by the rate of rise of voltage $dv/dt$. E. Warburg[4] concluded from experiments that ultra violet light reduces only the time lag of the spark because of the photoelectric effect, *i. e.*, the liberation of electrons from the cathode by light.

Townsend,[5] who developed the theory of ionization by collison, summarizes his views as follows: "In order to start a discharge it is necessary that there should be some ions in the gas initially, and when the force in the field between the electrodes is raised to a certain point, these are multiplied by collison to a sufficient extent to maintain the discharge.[6] At first the negative ions alone generate others as they move through the gas, but as the force increases and the sparking potential is approached, the positive ions also acquire the property of producing others to an appreciable extent."[7] In his theories, Townsend does not attempt, quantitatively, to account for time lag of spark discharges. He merely states that time lag is a direct function of the initial ionization of the gas and an inverse function of the overvoltage. Attempts have been made, however, to extend Townsend's theory to account for time lag of sparks, but none has been successful in accounting for time lags of a shorter period than $10^{-7}$ seconds which experimenters, such as Pedersen,[8] Peek,[9] and Burawoy,[10] find to exist at atmospheric pressures and large gap lengths.

W. Rogowski[11] has made a thorough analysis of the time lag problem, and has applied Townsend's theory quantitatively to a homogeneous field. In his calculations he assumes that the field contains at least one free electron which starts the ionization process. The time of breakdown was taken to be the time for the current to reach twice the value which would have been obtained if there was no ionization by collison of positive ions. This time is found from the determination of the rate of ionization, the respective velocities, and the distance traveled by both the positive and negative ions. The calculations are carried to a fair degree of refinement. The results he obtained show that the doubling of the current is reached after a time interval of $d/u$ in which $d$ is the distance between electrodes (in his case 1 cm.) and $u$ the velocity of the positive ion (which he found to be approximately $10^5$ cm/sec.). The time required to double the current would be of the order of $10^{-5}$ seconds. A discrepancy arises between the calculated and experimental time lag of spark formation.

Rogowski points out that the electron moves rapidly enough to transverse the entire field (1 cm. in length) many times during $10^{-6}$ seconds. The sluggishness of the positive ion causes much difficulty and is probably the weak point in Townsend's theory. Rogowski believes that space charge plays an important part in the breakdown, which would enable Townsend's theory to hold for surge breakdown by merely changing the number of electrons produced by positive ions in one cm. of travel.

## APPARATUS

For the study of impulse characteristics of gaps and other apparatus, it is necessary to have a controllable source of high-voltage impulses. Surges are usually produced artificially by discharging condensers through a resistance by means of a sphere-gap. The voltage piles up across the resistance which gradually discharges the condenser. The discharge may be a damped oscillation or a d-c. impulse, depending upon the value of the constants of the circuit. A surge generator of this nature, which the author used in studying time

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*Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

1. For references see Bibliography.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., February, 13-17, 1928.*

lags of sparks, was fully described by D. F. Miner.[12] Fig. 1 is a schematic diagram of the surge generator. It consists of ten groups of condensers, nine of which are charged in parallel through one-megohm resistors, and the first group of the series is charged directly without current limiting resistors. The purpose of eliminating the resistance in the first stage is to fix the potential of the charging apparatus to the voltage of the first group during discharge. $G_2$ is set to break down at a given voltage, while the other intermediate gaps, $G_1$, $G_3$, $G_4$, . . . . . $G_{10}$ are set for voltages approximately 25 per cent higher than $G_2$. When the condensers become charged to the voltage $E$, for which $G_2$ is set, the gap $G_2$ breaks down throwing groups two and three in series. The voltage now across the ends of these two groups is $2E$, which is above the breakdown voltage of the gaps at the terminals, consequently they too will break down. Thus, all the gaps break down in succession. Since there are ten groups charged to a potential of $E$, the final voltage across the terminals of the condenser groups will be $10E$. The rated voltage of each condenser group is 100 kv. Thus the maximum surge voltage obtainable without reflections is 1000 kv. By reducing the gap spacings a lower surge peak is obtained.

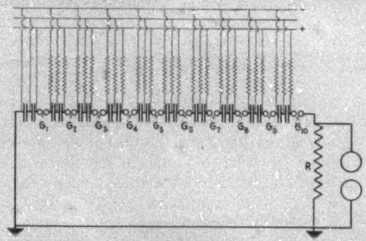

FIG. 1—DIAGRAM OF CONNECTIONS FOR 10-STAGE SURGE GENERATOR

### VISUAL EVIDENCE OF TIME LAG

The study of time lag demands a knowledge of wave form of the impulse obtained from the surge generator. While attempting to determine the wave front of steep waves by reflection methods, the author noticed that occasionally a glow resembling a corona discharge occurred between the 75-cm. spheres used as a measuring gap. It had been generally accepted in low frequency work that the sphere-gap flashover takes place without the initial corona formation that precedes a needle-gap flashover. The observance of this glow discharge led to a special study of the conditions under which it occurred.

The surge generator was connected directly to a transmission line 50 ft. long as shown in Fig. 2. The end of the line was grounded, thus causing the voltage at $G_3$ (75-cm. spheres) to be suddenly reduced when the wave reflected from the grounded end reached $G_3$; consequently the voltage impressed on $G_3$ rose very steeply and then dropped very sharply as a result of the reflection at the end of the line. Under these conditions, when trying to measure the crest of the voltage with a 75-cm. sphere-gap at $G_3$, a glow, instead of a spark, appeared between the two spheres. This phenomenon showed that the voltage was so quickly reduced to a negligible value after ionization began that a complete spark was prevented from forming.

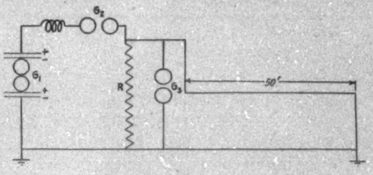

FIG. 2—DIAGRAM FOR USING TRANSMISSION LINE

### IMPROVEMENT OVER TRANSMISSION LINE

The voltage wave impressed upon the sphere-gap was then of the nature shown in Fig. 3. The ionization by collision would probably start before $E$, but the developed spark might not occur until point $f$ was reached due to the time lag of the sphere-gap. If the voltage was brought to zero somewhat faster, the developed spark might not occur at all, even though the air between the spheres would be sufficiently ionized to cause a luminous glow. Since the wave shape obtained in this way had such a flat top, conditions were quite critical, and therefore any slight overvoltage or decrease in spacing of the spheres caused a complete breakdown, while if the voltage did not quite come up to that for which the spheres were set, no luminous discharge would occur at all. A less critical arrangement was found by using a second sphere-gap, $G_4$ Fig. 4, instead of the grounded transmission line. This circuit was a great improvement over the original one as it was much more flexible. By varying the setting of the second sphere-gap $G_4$, it was possible to obtain a photograph of the discharge in the first gap

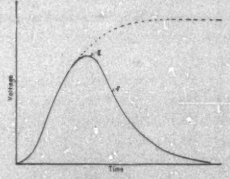

FIG. 3—GENERAL SHAPE OF WAVE IMPRESSED ON SPHERE-GAPS

$G_3$ in any stage of its development. The second sphere-gap reduced the voltage to a negligible value much more rapidly than was possible with the transmission line, where the wave front was the controlling factor. An example of a discharge across the first sphere-gap obtained in this way is shown in Fig. 5.

From the known characteristics of the surge front, a fair conception of the time required for a streamer to bridge a 40-cm. gap was obtained. This time using 75-cm. spheres was found to be of the order of $10^{-8}$ seconds. The wave used had a rate of rise of approximately 5000 kv. per microsecond. Thus, knowing the sphere-gap settings (and their corresponding static spark-over voltages) at which suppressed discharges first appear and the maximum separation at which complete spark-over is obtained, the time elapsing between the two periods can easily be found.

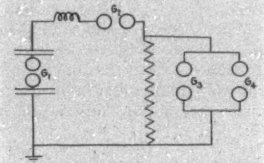

Fig. 4—Method for Utilizing Sphere-Gap Instead of Transmission Line

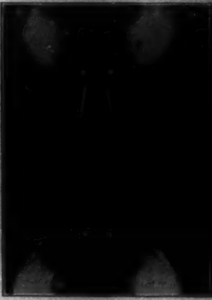
Fig. 5

Fig. 6

Fig. 4—A Typical Suppressed Discharge in which Cathode is Grounded

Fig. 5—Suppressed Discharge with Anode Grounded

Discharges of the nature shown in Fig. 5, or "suppressed discharges" as they might be termed, give much information concerning the process of breakdown. The bright streamers on the ungrounded positive sphere in Fig. 5 span only a portion of the distance between the spheres. The rest of the gap is bridged by a light purple haze. Differences in intensities of luminosity of various portions of the field indicate in a rough way that the state of ionization is not uniform throughout. It is probable that the bright anode streamers have already the properties of arcs[3] while the haze extending from the ends of the streamers to the cathode is still a glow discharge. Evidently then, the breakdown starts at the most intense portion of the field (assuming a uniform density of free electrons throughout the field) and progresses into the field until it meets a streamer developing from the electrode of opposite polarity. In the case of sphere-gaps, when one sphere is grounded, the gradient at the surface of the ungrounded sphere is much higher than the gradient on the grounded sphere. This fact is clearly illustrated by Figs. 5 and 6. In Fig. 5 the cathode is grounded while in Fig. 6 the anode is grounded. The streamers on the grounded sphere have developed but little, showing a weak field at that point. These figures indicate rather clearly that a spark develops from a dark current to a glow discharge which in turn assumes the properties of an arc at points where the current densities are highest.

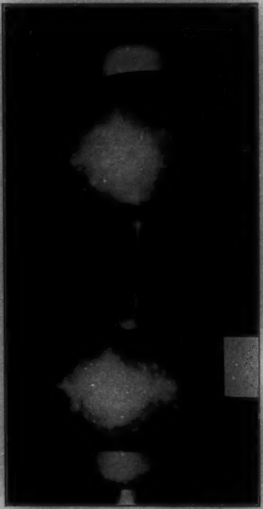

Fig. 7—Streamers Affected by Space Charge

## SPACE CHARGE

Under atmospheric conditions comparatively low voltage is necessary to maintain arcs. Thus when a streamer develops into an arc it has the effect of a needle extending into the electrostatic field. The field form under these conditions will change, resulting in the development of new streamers and an acceleration in their rate of development.

The manner in which the development of slower streamers is affected by the change in field form is shown in Fig. 7. The upper or cathode streamers are concave outwards. The center streamer, having probably started first and developed faster than the rest, reduced the gradient between the tip and the sphere from which it developed, and caused the lines of force of the electrostatic field to be concave outwards.

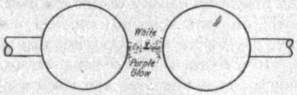

Fig. 8—Formation of Streamers in Space Between Electrodes

Most theoretical determinations of time lag of sparks assume a fixed homogeneous field throughout the entire process. These assumptions do not hold beyond the time when a streamer forms. As pointed out herein, these streamers are in effect conductors extending into the electrostatic field. Since the entire potential appears at the tips of these streamers, the spacing between electrodes will be materially reduced, producing an increase in the gradient between the anode and cathode streamers. The maximum gradient appears at the tips of the streamers because they can be considered as needle electrodes. As the streamers grow the gradient increases, and since the rate of ionization is a function of the gradient, the streamers must develop more rapidly in the more advanced stages. Thus, the development of the streamers cannot be considered as uniform.

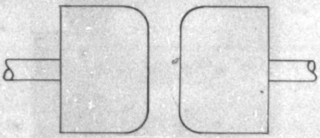

Fig. 9—Electrodes Used to Obtain Homogeneous Field

Suppressed discharges have been obtained on gaps varying from 0.25 cm. to 75 cm. spacing. For voltages ranging below 100-kv. crest, 6.25-cm. spheres were used; then for potential ranging between 100 kv. and 500 kv., 50-cm. spheres were utilized. For all voltages above 500 kv., 75 cm. spheres were used. While observing these discharges, on small spacings (0.25 cm. to 2-cm.) several discharges occurred which had their intense streamers in the center with a faint glow extending from both ends to the electrodes. Fig. 8 illustrates this phenomenon.

This type of discharge was obtained only after several lower voltage surges, not resulting in breakdown of the air, were impressed on the spheres. Several explanations for the phenomenon were considered, the following two being the most logical; first, that the location of the first streamer is a matter of probability, and the resulting variability in its location becomes more marked as the initial number of free electrons in the field diminishes; second, that a current of air carries out the air ionized by application of voltage below the breakdown value, replacing it with air containing the normal number of free electrons. The surface friction prevented the air next to the electrodes from being swept out. When a surge of higher amplitude than the rest was applied, the air in the center of the gap became ionized to a higher degree than that at the surface, due to the greater initial number of free electrons at that point. As ionization progressed, a streamer formed in the center, but before it could reach either electrode, the voltage was reduced by the suppressing gap.

Should the second explanation be correct, it would mean that the breakdown (at least with very steep surges and normally ionized field) is not produced by electrons traversing the entire field but that each portion of the field is ionized separately by the local ions, these sections being joined together as the streamer progresses.

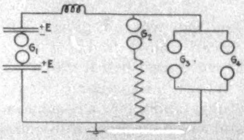

Fig. 10—Scheme for De-Ionizing Air Between Spheres by Condenser Potential

Using spherical electrodes this phenomenon was reproduced quite often, *i. e.*, 1 out of 10 times. Again when the field distribution is considered it is difficult to attribute this type of suppressed discharge to probability. The highest gradient is at the surface of the spheres, while the gradient at the center is appreciably lower; thus the velocity of the electrons and positive ions will be higher near the surface than in the center and more electrons will be produced there. With higher density of free ions near the surface, the probability of the arc originating at the center would be much less. However, when electrodes of the type shown in Fig. 9 were used, the phenomenon occurred 3 out of 10 times, the gradient throughout the field being more nearly homogeneous than with spheres, which gives the probability theory more weight.

## The Effect of Varying the Initial Density of Ions

The original number of ions in the field can be varied by two means,—by controlling a source of ionization and by drawing the free ions out of the field. The latter can be effected by impressing a constant voltage below breakdown value on the electrodes. In applying the first method, soft X-rays were used to ionize the field. The set-up used is shown schematically in Fig. 10. Gaps $G_3$ and $G_4$ had a constant potential impressed upon them, which in this case is always the condenser charging potential $E$. When $G_1$ broke down the two banks of condensers were thrown in series, impressing $2E$ on gaps $G_2$, $G_3$, and $G_4$. In this manner surges were applied to sphere gaps which were constantly excited. Under these conditions the number of ions in the field just before breakdown was reduced to a very small quantity. $G_3$ was set slightly above the breakdown value of $G_1$ so that $G_1$ would break down before $G_3$. $G_4$ was used to measure the voltage and under suitable conditions would show suppressed discharges appearing across $G_3$. The results of this test are tabulated in Table I. Under these conditions, suppressed discharge at $G_4$ could rarely be obtained, and even then the glow at the ends of the streamers was very faint. The maximum voltage indicated by $G_4$ was 66 kv. X-rays were directed on $G_4$ Fig. 10 to increase the ionization in the gap. Now, however, the spacing in $G_4$ had to be increased to 3.18 cm. before complete breakdown ceased. This setting corresponds to 81 kv. Suppressed discharge appeared up to a separation of 3.8 cm. or 89 kv. The glow at the tips of the streamers was now very pronounced. These two tests indicate rather strongly that the time lag of sphere-gaps is a function of the number of ions in the field when the surge is applied. The prominence of the glow at the ends of the streamers

TABLE I

| Conditions | $G_1$ |  | $G_2$ |  | $G_4$ |  | Remarks |
|---|---|---|---|---|---|---|---|
|  | Sep. in. cm. | Kv. | Sep. in. cm. | Kv. | Sep. in. cm. | Kv. |  |
| Excited<br>No X-rays.. | 1.68 | 50 | 1.9 | 57 | 2.33 | 66 | Complete flashover on $G_4$ ceased at 2.33-cm. spacing and suppressed discharge occurred very seldom above that value. |
| Excited<br>X-rays on $G_4$ | 1.68 | 50 | 1.9 | 57 | 3.18<br>3.8 | 81 | Complete flashover ceased on $G_4$ for separations above 3.18 cm. but suppressed disharge appeared from 3.18 cm. to 3.8 cm. |

FIG. 11—RARE FORM OF SUPPRESSED DISCHARGE

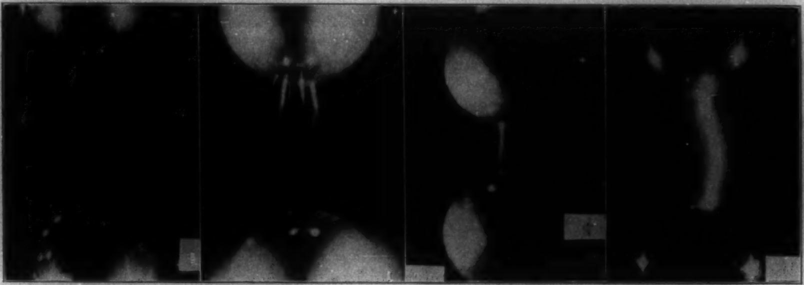
FIG. 12 FIG. 13 FIG. 14 FIG. 15

FIGS. 12, 13, 14, 15—SUCCESSIVE STAGES OF BREAKDOWN OF AIR

12 Early stage
13. Secondary stage
14. Space almost spanned by streamers
15. Complete discharge

in the case of previously ionized gaps together with the increase of speed of breakdown is in full accord with the assumption that the free ions originally in the field produce numerous ionized sections which finally join to form streamers. The rapidity of development of these streamers might be taken as a function of the number of these ionized sections.

Fig. 16—Electrostatic Field Around Insulators Modified by Arcing Ring and Arcing Horn

## ELECTROSTATIC FIELD DETERMINATIONS

It seems possible to study the progressive stages of breakdown by the *suppressed discharge method*. This will yield important information as to the character of breakdown with various type of apparatus. Fig. 11 portrays a rare type of streamer development. The streamer starts at the side rather than in the center and develops according to the electrostatic field at that point. This cut reveals the effect of the earth upon the electrostatic field between the spheres.

Fig. 17—Field Around Insulators as Improved by Circular Arcing Rings

Figs. 12, 13, 14, 15 were selected from a large number of tests as representing progress of breakdown from initial streamer formation to arc-over.

One application of the suppressed discharge which has proved useful in engineering work is shown in Figs. 16, 17, and 18. A picture of the electrostatic field surrounding an insulator string at the time of impulse application is produced and shows the corrective or destructive effect caused by use of special transmission fittings. In Fig. 16 a horn was used at the top and a ring at the bottom of an eight unit string. The concentration at the horn tips is shown and also the drawing-in of the field at the top of the string. This leads frequently to cascading flashover. In Fig. 17 two arcing rings were used and the field is much im-

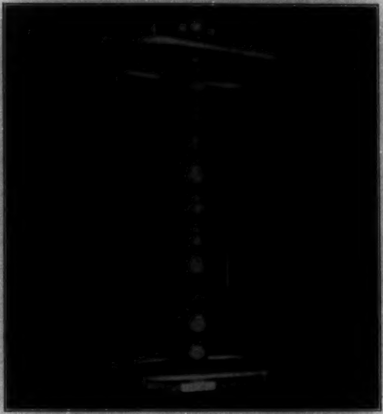

Fig. 18—Electrostatic Field as Modified by Elliptical Rings

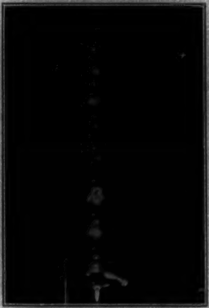

Fig. 19—The Early Stages of Insulator Flashover

proved. A flashover clear of the string will result from this field. Special elliptical rings were attached in Fig. 18 and the resulting field is well distributed.

Fig. 19 reveals the manner in which a string of insulators cascade. The bottom insulator is already shunted by a streamer, while the one above it is just in the process of cascading. A streamer is forming from the cap of each of the two bottom insulators. The streamer progressing from the cap of the one next to the bottom is barely visible. Unfortunately the streamers develop much more rapidly in the latter stages making it very difficult to obtain suppressed discharge after the streamers have spanned a third of the spacing between the electrodes. Thus a complete story of dielectric breakdown by this method is almost impossible, but much can be learned from the earlier stages of development.

The writer wishes to express his appreciation to Dr. J. Slepian for many suggestions and comments which have been of great assistance in carrying on this work and in preparing this paper, and also to Messrs. Fortescue and Tenney for their valuable criticisms.

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## Discussion

**C. L. Fortescue:** I will bring out some important practical deductions from the results Mr. Torok obtained with the suppressed flashover of spheres.

First I want to review what he found for these spheres. The stages of breakdown are: 1, free electrons are drawn into the field; 2, free electrons are increased by ionization by collision, recombination taking place also; 3, a critical stage is reached where the rate of ionization and volume density of the free electrons has reached a critical point, which shows itself in the emission of ultra-violet rays. This results in the final stage when it is believed that molecular dissociation of the air molecules takes place, which is shown by intense white streamers which form at the electrode having the highest intensity, and these streamers grow outward from the electrode and finally grow together and cause the breakdown. The growth of these streamers takes place progressively from the electrode outward, and it apparently has a velocity of propagation which is proportionate to the difference of potential between the electrodes, so that from this point on the breakdown takes place as a function of time. It is not instantaneous but takes an appreciable time.

This is the factor which is responsible for the fact that with very steep wave fronts an insulator, or a string of insulators, has what is known as an impulse factor. That is to say, it breaks down at a higher value than the normal 60-cycle flashover.

I wish to show the reason for this by means of the accompanying Fig. 1. The steepness of the wave fronts is shown by straight lines, and the slope determines the steepness. The surges we consider are surges which would keep on rising if the insulator or spark-gap did not flash over. The horizontal line shows the voltage at which the insulating string or sphere-gap will have reached the critical stage, where, you might say, it is just at the point of breaking down.

Breaking down is not an instantaneous process; it takes time. So during the time while the breakdown is taking place the voltage is still rising, and the actual arc-over will take place at some higher voltage, the magnitude of which will depend upon the character of the insulator or spark-gap. Now if we were to have a wave which just reached the 60-cycle flashover or critical point, and then remained at that voltage for an appreciable length of time, and then came down, the flashover would take place at some appreciable time from the point at which it reached that voltage, and the potential recorded would be the same as the 60-cycle flashover potential or slightly higher. However, if the same wave had been still going up, the voltage recorded would not be the 60-cycle voltage but the flashover would take place at some time after this stage had been reached and at a higher value. This time can be calculated by the velocity at which these streamers come together.

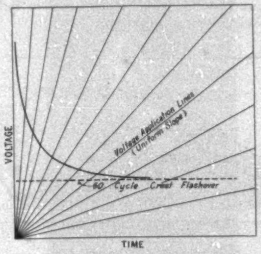

Fig. 1—Time-Voltage Flashover of Insulation

The steeper the wave front the higher the voltage that will be reached before those streamers come together. But the velocity increases with the potential, and the actual time that elapses between the critical point and the point of flashover becomes somewhat less as the steepness increases, so that we can figure out the points for each steepness and we will get a curve like that shown in Fig. 1. That is what Mr. Torok's results indicate, and as a result of his work we have been able to calculate the flashover curve for different steepnesses of wave front of strings of insulators, and have been able to duplicate those results by actual observations very closely. In fact the curves check so well that the discrepancies are within the errors of observation.

Another important thing that this shows is that the sphere-gap always has a time lag, though this happens to be very small. The sphere-gap is not instantaneous. From the results of Mr. Torok's tests I have made some calculations on the probable impulse factor of the sphere-gap. For instance, for a wave front which has a steepness of about 10,000 kv. per microsecond, the impulse factor would be about 1.05. The steepest wave we get in lightning does not go much above 4000 kv. per microsecond, and at that value the impulse factor is probably not more than 1 or 2 per cent above unity at the most, so that we can always rely on the sphere-gap to give the correct surge potential for all waves that we are likely to get in service, and therefore for all practical waves in the laboratory. We can, of course, produce waves in the laboratory that have a much greater steepness than those that are encountered in lightning.

Now one more point. These results of Mr. Torok also throw a great deal of light on the phenomena of lightning. Mr. Simpson, one of the British authorities on lightning, has shown, at least he has satisfied himself, that certain experiments which he has made indicate that when a cloud is negatively charged the lightning stroke will start from the earth instead of the cloud. His experiments have convinced him that this is true, and he has also shown photographs supporting this point of view.

In Fig. 2 herewith, is shown a cloud about 1 km. above the earth's surface. Simpson says that the lightning discharge starts in the earth and goes up and then branches out into a portion of the cloud and discharges this portion of the cloud. He claims that when the cloud is positively charged the stroke does not branch out and only a very small portion of the cloud is discharged. And therefore, he says that the severe discharges from the clouds are all negative. Apparently this is true, for we have always found in our field investigations in lightning that all the severe discharges were negative.

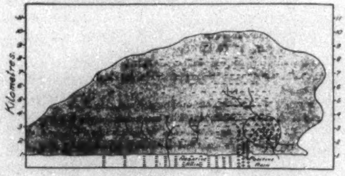

FIG. 2

Let me point out what probably occurs as a result of Mr. Torok's investigations with spheres. These streamers do form at the earth and they are propagated toward the cloud at a certain velocity which is quite fast. We don't know just what it is between cloud and earth but between spheres it happens to be about one-tenth the velocity of light. The cloud is not discharged when the streamer reaches the cloud. That is only the beginning of the discharge. All that has happened is that a conducting path has been formed between the earth and the cloud. After this is formed, a part of the cloud discharges to the earth in the form of a surge. In other words a dynamic surge is formed along the path that has been made, conducting by this first, initial streamer, a condition which Mr. Torok describes. So that when this portion of the cloud is discharged a wave or surge is set up which, if it strikes a transmission line, is already dynamic and divides into two ways forming the surge encountered in lightning. This surge, being dynamic, does not reach as high values as if it were simply a case of a certain charged capacity in the cloud combining with the capacity of the transmission line to produce a potential on the line, but the dynamic surge divides and is reduced thereby. Otherwise it would be very hard to account for the fact that a great deal more damage is not done by lightning. The potentials of the clouds are so high that one would expect very much higher potentials in surges than actually appear, if the phenomena were the same as that of the discharge between two condensers, one of which is charged to a high potential and the other is uncharged.

The foregoing gives, I believe, a correct scientific explanation of the lightning discharge, and one which will account for the surge potentials which are encountered in the field.

**J. A. Duncan:** Mr. Torok refers to Rogowski's analysis of the time lag problem on the basis of the Townsend Ionization by Collision Theory. Rogowski has, as Mr. Torok says, been rather careful with his mathematics and I shall assume that it is correct. After reading his paper, my understanding of his conclusions is as follows:

A few electrons are assumed to be present in the air previous to the application of the electric field. A field of 30,000 volts per cm. is suddenly applied. The electrons acquire velocities which on the average are of the order of magnitude of $V = 4.3 \times 10^7$ cm./second. This means that an electron will move completely across the gap, which in his case was one centimeter, in about $2.3 \times 10^{-8}$ seconds. In so doing, it will ionize a great number of molecules, each of which gives rise to one new electron and one positive ion. These new electrons will all immediately proceed to move towards the anode and acquire velocities comparable to $4.3 \times 10^7$ cm./sec. and will in turn each produce a great many more new ions by collision as they go. The new positive ions, on the other hand, move toward the cathode with velocities only of the order of $U = 0.96 \times 10^5$ cm./sec. and will take several hundred times as long to get under way to the extent of producing further new ions by their collisions with molecules.

Breakdown is assumed to have occurred when the current reaches a value twice as great as that which would result from the ions produced by collision of negative electrons only. In other words, it occurs after the positive ions begin to have an appreciable effect, according to his picture. The time is too long in comparison with experiment simply because the positive ions move relatively slowly.

The question naturally arises whether there is some other secondary agency which begins to produce new ions and hence aid in the increase or doubling of the current long before the positive ions begin to have an effect.

According to Haas, (Introduction in Theoretical Physics, Vol. 11, Par. 119) it requires several times as much energy to ionize an atom into positive and negative ions as it does to excite it to a condition such that it can radiate light. This excitation consists of knocking an electron out of its normal orbit to an outer orbit, from which it may later fall back. The electron remains in the outer orbit for a time whose order of magnitude is $10^{-8}$ sec., according to Haas, and then falls all or part of the way back to its original orbit and in so doing, emits light. This light will be scattered in all directions, some falling on each electrode. Suppose some of this is ultra-violet light. In this case, new electrons will be emitted by the photoelectric effect at each electrode. Those emitted from the cathode are available for a very marked increase in the current which increase can take place in less than $10^{-7}$ seconds. The elapsed times occurring are as follows, for the one cm. gap:

Time for 1st set of electrons to each anode . . . . = $2.3 \times 10^{-8}$ sec.
Time allowed for emission of light . . . . . . . . . . . = $1 \times 10^{-8}$ sec.
Time for passage of light to cathode

$$= \frac{1}{3 \times 10^{10}} = 0.33 \times 10^{-10} \text{ sec.}$$

Time for second set of electrons to reach anode . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . = $2.3 \times 10^{-8}$
Total elapsed time . . . . . . . . . . . . . . . . . . . . . . . . = $5.6 \times 10^{-8}$ sec.

In this connection it is interesting to note that the photoelectric effect, *i. e.*, the emission of electrons from the surface of metals on which ultra-violet light is allowed to fall, was discovered by Hertz when he observed that the light from one spark-gap between aluminum electrodes in air had an appreciable effect on the ease of discharge of a second gap if this light fell on the electrodes.

What I am now suggesting is simply that it seems conceivable to me that in a single gap there might exist a similar effect even in a time shorter than $10^{-7}$ sec.

Mr. Torok has made a much deeper study of breakdown phenomena than I have and I trust he will be so kind as to tell us whether such a supposition, in the light of his experience, is conceivable to him.

**Joseph Slepian:** Mr. Torok in his paper brings out that the Townsend theory of breakdown in spark-gaps apparently fails at atmospheric pressures when the speed with which the spark-gap breaks down is considered. In the mechanism required by the Townsend theory, time of the order of $10^{-5}$ or $10^{-4}$ sec. would be required for breakdown. The pictures which Mr. Torok has obtained seem to point out also pretty definitely that the Townsend mechanism does not hold at atmospheric pressure, and they suggest what may be the way out of the difficulty. The Townsend mechanism apparently works very well at low pressures. It requires electrons moving toward the anode to ionize by collision, and also requires the positive ions generated by collision to return towards the cathode. The return of these positive ions is necessary in order to bring out by collision a new and increased supply of electrons to carry on the breakdown process. But it is the slowness of the positive ions in returning toward the cathode that causes the difficulty with the application of the Townsend theory to breakdown at atmospheric pressures.

According to the Townsend mechanism it would seem that the conductivity should develop over the whole breakdown path in a rather uniform manner. That is, the whole path should first become slightly conducting, and then more and more highly conducting. The pictures of suppressed discharges should then give either faint breakdown paths or more intense breakdown paths. The pictures actually show the path completely broken down in one part and not at all broken down over the remainder. They show that the breakdown progresses rapidly across the gap, being almost complete over part of the gap before it begins in other parts of the gap. The pictures strongly suggest that the single passage of the initiating electron across the gap is enough to give breakdown. According to the Townsend theory when the single electron goes across the gap and is accompanied by its tremendous progeny of electrons that it generates on the way, the initiating electron and its descendants all travel together and leave behind them only a trail of slow-moving positive ions, which could hardly be called conducting.

But Mr. Torok's pictures suggest that the trail which the initiating electron does leave behind is highly conducting. A possibility which occurred to me is that at atmospheric pressures the multiplication by collision of the initiating electron is so rapid and the multiplication takes place in a path of such small section, that the mere passage of it, with its accompanying new electrons, is enough to raise the temperature of the path to a high degree and to leave behind a path that is at such high temperature that it is thermally ionized, and continues to be ionized by virtue of high temperature.

On this basis, I have calculated what the temperature would be in the path traversed by the initiating electron, and was rather surprised to have it come out sufficiently high. In fact, on this basis I was able to check quite closely the values for breakdown of spark-gaps at atmospheric pressure, and also to get the right order of magnitude for the time of breakdown.

I believe that a very valuable part of Torok's work is in the suggestions which it leaves for future work, such, for example, as taking into account the temperature rise in the path of an electron, as I have attempted to do.

**F. W. Peek, Jr.:** I began to study this subject about 1913 and in 1915 presented a paper before the Institute on the *Effect of Transient Voltages on Dielectrics*. (See TRANS. A. I. E. E., Vol. XXXIV, part II, 1915, p. 1857. Cathode-ray oscillographs that could record transients of short duration were not available so it was necessary to devise an impulse generator for which the waves could be calculated. Such a generator was devised and we were able to determine time and time-lags for all types of gaps, insulation, insulators, etc. It was found that these time-lags came conveniently in millionths of seconds. For this reason the term "microsecond" was used and found to be an exceedingly convenient unit.

The early work with this lightning generator showed that the impulse sparkover or breakdown voltage was always higher than the 60-cycle or continuously applied breakdown voltage due to the time-lag. The ratio between the impulse breakdown voltage and the 60-cycle voltage was called the "impulse ratio." This term is still used to indicate the relative values of insulation for lightning or impulse breakdown. The higher this ratio under given conditions the greater the lag. This research showed that for electrodes giving an approximately uniform field, as for instance the sphere gap, the lag was small or the impulse ratio was approximately unity over a large range of impulses. It also showed that for irregular fields the lag was appreciable and the impulse ratio increased with the steepness of the wave front. In other words, it was found that the lag was not constant but varied with the duration or rate of application of the voltage as well as with the type of electrode used. Since the impulse ratio of the sphere-gap approximated unity except for the very steepest waves, it offered a means of measuring transient voltages and has been an almost indispensable tool in such investigations.

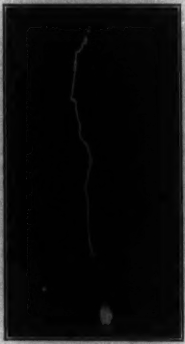

FIG. 3

This early investigation was carried up to about 200,000 volts. Since then the work has been carried on to considerably over 2,000,000 volts. Recently I have been able to obtain actual oscillograms of the calculated time-lags and waves of the original investigation. These measurements were made with a cathode-ray oscillograph of the Dufour type developed in our general engineering laboratory at Schenectady.

The oscillograms checked our early work very well. Similar oscillograms have also been made of the very high-voltage waves with a similarly good check of the calculated values.

A great deal of practical value came out of this early investigation. For instance, since the sphere-gap had practically no time-lag it offered an ideal lightning-arrester gap. On the other hand the information made it possible to design bushings and insulation with high time-lag or great lightning strength.

The more recent work at the higher voltages has also been of practical value in determining the best means of building transformers and other apparatus to resist lightning. One instance that might be mentioned is the grading shield for insulators which is of particular value at high voltages, since it not only prevents cascading but also increases the lightning arc-over.

Mr. Torok's pictures showing the value of the grading ring are quite interesting and confirm my own work.

I have also observed the partial or incomplete lightning arcs due to transients of short duration. The accompanying Fig. 3 is a good example of this. In this figure the completed arc is shown as well as other incomplete arcs along the lines of force between the gap. In the course of my investigations I have obtained similar photographs of bushings, insulators, etc. I hope that Mr. Torok will be able to continue his very interesting work.

**H. J. Ryan:** (by letter) Mr. Torok's unique experiments made by a new mode of procedure yielded important results which are placed in the light of a clear understanding. These are the pioneer group of a long line of experiments that will follow quickly, now that the value of the "arrested" method is so well demonstrated. The role of the space charge in the Townsend theory of ionization by collision whereby the heavy positive ions also attain velocities high enough to produce other ions by collision, has been clearly emphasized. The participation of the positive as well as the negative ions is necessary in the process of sufficiently augmenting ionization by collision to retain the Townsend theory in accounting for the enormous conductivity that is known to develop with great suddenness in sparkover. In addition to local citations by Mr. Torok, see the brief paper on "Ionization by Positive Ions," in the December 23, 1927 issue of *Science* by Dr. Leonard B. Loeb and his more extended paper on "Theory of Electrical Breakdown of Gases at Atmospheric Pressure," soon to appear in the *Journal* of the Franklin Institute of Pennsylvania. In concluding the latter paper, Dr. Loeb says "experiments should be undertaken in laboratories equipped for the purpose to look for both the spark-lag and the non-uniform field."

It is of great practical as well as theoretical value to know the facts about the time-lag and the other essential physical characteristics of sphere-gap discharges. The result recorded and discussed in connection with Fig. 8 well authenticates the important fact that the blue-white channel which grows into a sparkover with enormous suddenness is formed of dissociated air without the presence, necessarily, of electron-laden metallic vapor drawn from the electrodes. When not too explosive the spark merges later into an arc pervaded by metallic vapor. The time factor in the rapid production of the high conductivity of the spark channel is well established in the paper. The impedance of all ordinary high-voltage sources having small terminal capacitances is too great to accord sufficient current acceleration, $di/dt$, to develop strong sparks. Only when the capacitances of the electrodes are relatively large can the current acceleration be great enough to develop sparks that are strong enough to be easily distinguished from the arcs that follow.

To date, then, it appears that sparkovers are due to highly conducting channels of electrically broken down or dissociated air produced when the intensity of migration of ions formed in corona exceeds a critical value. The voltage consumed in producing this critical intensity of migration of corona ions in the air at 25 deg. cent. and 76 cm. pressure is approximately 4 kv. eff. per cm. or 10 kv. eff. per in. At higher driving voltages the ionized air is electrically dissociated so as to become suddenly enormously more conductive. The magnitude of the conducting channels thus established is largely determined by the strength of the current that the impedance of the rest of the higher-voltage-source circuit will permit to flow. Many able physicists are at work upon the intimate characteristics of this greatly enhanced ionization that results in sparkover and which for present purposes we are calling *electrical dissociation.*

That air may become electrically dissociated and rendered enormously conductive can be conveniently demonstrated in the high-voltage laboratory by using nitrogen-filled incandescent lamps as discharging electrodes. The lamp bulbs are mounted axially with their convex walls face to face and separated by a short distance, 1 to 3 in., according to size. On applying to them gradually increasing voltage, a value of voltage is soon found at which the nitrogen goes into corona and an abundant supply of ions is thus produced. The space charges that result within the bulbs migrate to and are bound at the inner faces of the opposing bulbs to form a strong field between them through the open air. Such air then goes into corona too, copiously forming ions that are made simultaneously to migrate with an intensity that exceeds the critical migrating intensity resulting in the dissociation which forms the highly conducting blue-white channels characteristic of sparkover. The channels separate and convey the ions to respective outer bulb-wall to be bound to the opposing charges existing on the inner bulb-walls. Thus sparkovers are produced between glass walls as electrodes with no possibility of electron-laden metallic vapor taking part. In performing this experiment care must be taken to shut off the supply voltage quickly after the sparks between the bulbs have been started, otherwise the pyroelectric effect that follows will produce thermal punctures. It is well to remember that additional condensers connected between the electrodes or better, perhaps, between each electrode and ground will increase the available current acceleration necessary for well defined sparkover action.

This sparkover experiment with the nitrogen-filled incandescent lamps was suggested by Bradley Cozzens of our present high-voltage laboratory staff.

FIG. 4—ELECTROSTATIC FIELD OUTLINED BY CORONA DURING IMPULSE TESTS ON A 73,000-VOLT OIL FILLED BUSHING SUBJECTED TO IMPULSES OF 850,000 VOLTS

**E. D. Eby:** (communicated after adjournment) Mr. Torok's observations concerning the study of the electrostatic field by means of the suppressed discharge as illustrated in Figs. 16 to19 of his paper remind me of a similar study which I made in 1924.

At that time we were investigating the impulse flashover of high-voltage bushings of the oil-filled type. These bushings offer a splendid means for study of impulse phenomena because they are immune from damage under such impulses and may be tested repeatedly without failure. Among the interesting tests we made were some arranged to show the distribution of the electrostatic field around the bushing under impulse conditions. The distribution under 60-cycle conditions had been observed repeatedly and had actually been measured and plotted. It was, of course, out of the question to measure the distribution with impulse voltages, but we found we could photograph the electrostatic field and thus secure a very fair idea of its distribution. By applying impulses of different magnitude up to and including the flashover voltage, and by photographing the corona formed by these impulses with a special lens and rapid film, we were able to secure a very good idea of the electrostatic field under impulses.

In Fig. 4, herewith, there is shown a photograph of a 73,000-

volt oil-filled bushing subjected to about 850,000 volts. This is below the flashover voltage of the bushing, and the discharges at the most intense points of the field reach only a short distance into space. The shape of the field is well outlined by the corona. A similar view taken during the same series of tests was published in the *Electrical World* June 12, 1926. The more intense illumination of the film was produced in that instance by applying ten successive impulses during the exposure.

In Fig. 5, herewith, there is shown a view of the electrostatic field surrounding an 88,000-volt oil-filled bushing when subjected to impulses of about 1,000,000 volts. This view is particularly interesting in showing the concentration of the luminous field at points on the electrodes. Just above the porcelain shell, shafts of light are seen emerging from the surface of the clamping ring, these spots probably indicating small beads on the surface of the casting. Likewise, below the porcelain shell the concentration of the field upon the heads of the clamping bolts is very conspicuous.

During the same series of tests, impulses were applied to the bushing, subjected to a spray of water, in accordance with usual wet-test practise. The voltage required to produce flashover under these conditions was approximately the same on the average as required when the bushing was dry. This fact is of special importance in a discussion of the performance of bushings under service conditions. It demonstrates that the wet flashover voltage of a bushing is of interest only in terms of the system frequency. If the wet flashover is of such value that it exceeds any low-frequency potential that can occur on the system, there is nothing gained by increasing it further. Since voltages of the order of magnitude of flashover of bushings of good design occur in service only under impulse conditions where the wet and dry flashover voltages are the same, it becomes of prime importance to relate properly the impulse flashover of the bushing to other insulations on the system and particularly to the puncture strength of the bushing itself under impulses. Beyond question, a bushing should be self-protecting under impulse voltages as well as at system frequency, so that it may withstand impulse flashover without puncture in service.

FIG. 5—ELECTROSTATIC FIELD OUTLINED BY CORONA DURING IMPULSE TESTS ON AN 88,000-VOLT OIL FILLED BUSHING SUBJECTED TO IMPULSES OF 1,000,000 VOLTS

The illustrations in Mr. Torok's paper in which insulators are shown, and the accompanying pictures of similar tests on oil-filled bushings illustrate also why the impulse ratio of these devices is approximately the same as that of the needle-gap. The wide departure from uniformity in the distribution of the electrostatic field permits portions of the space near the electrodes to become completely conducting before the intervening region has become sufficiently stressed to permit discharge. If a design of bushing or insulator approaching a sphere-gap in characteristics were to be subjected to impulses, the impulse flashover voltage would be relatively lower. Such a bushing or insulator having a normal 60-cycle flashover voltage would invite premature flashover under impulses. For this reason, a bushing with a high impulse ratio is desirable—that is, one having an impulse voltage comparable with that of other gap spacings on the sys'em. While points on the electrodes of a bushing will reduce its 60-cycle flashover, they serve the more important function of maintaining a high impulse ratio.

**K. B. McEachron:** (communicated after adjournment) The method of studying the breakdown of air under impulse conditions given by Mr. Torok, sheds further light on the mechanism of the propagation of lightning through the earth's atmosphere. A more complete understanding of how the breakdown between the cloud and earth is accomplished would aid materially in determining the effects on electrical circuits located within the cloud field. It has been stated, based on Simpson's theory, that the discharge of a positive cloud is slow and therefore not harmful to the electric circuits and apparatus involved. On the other hand, discharges from the negative cloud are abrupt and give rise to dangerous voltages on transmission circuits. These statements are said to be determined from the results of klydonograph studies on transmission lines in which the highest voltages are found to be negative, indicating direct strokes, and the smaller voltages positive indicating induced charges, but from negative clouds.

If it were known that the negative discharges were the result of direct strokes and conversely that all of the direct strokes produced negative figures, the case would be somewhat more definite, but unfortunately such correlation of data is lacking. Positive and negative surges have both been found of magnitudes indicating potentials on conductors of 1800 kv. or more. On some of the systems studied, almost no difference in potential was found between the positive and negative surges.

In the very nature of the case one would expect nearly always to have many more induced surges than direct strokes and consequently find one polarity predominating. Although on some systems this has been true, there have been notable exceptions. In view of the nature of the data yet available, it does not appear that any definite statement can be made as to the polarity of clouds which give rise to dangerous surges. The same cloud may have, of course, different polarities at different points within the cloud.

Studies similar to that of Mr. Torok's coupled with an investigation of the lightning discharge itself will do much toward reaching the true determination of the mechanism of the lightning discharge.

From the paper and the ensuing discussion, I gather the impression that the effects due to polarity are masked by the fact that one of the two spheres was grounded. If Figs. 5 and 6 of the paper are comparable, one would be inclined to the belief that with ungrounded spheres, a discharge would appear having a greater volume on the positive sphere than on the negative sphere.

When viewed through a stroboscope, 60-cycle discharges appear almost entirely on the positive conductor. A study was made of this discharge a few years ago at Purdue University.[1] Using a synchronous camera the corona discharge from a pair of needles was spread along a time axis. Occasionally when a critical potential was reached, a spark would occur which was associated with the positive needle but not always with the negative. The negative point during these tests always showed a very intense point of light. The investigation was conducted in two ways; one in which the field was alternately positive and negative, and the other in which the needle was moved synchronously so that any given location was subjected to a pulsating field always of the same polarity. With either method, it was found that the streamers and corona discharge were associated with the positive needle.

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[1] "A Photographic Study of High-Voltage Discharges," Bulletin No. 19, Engineering Experiment Station, Purdue University, Lafayette, Ind.

*Two Photographic Methods of Studying High-Voltage Discharges*, K. B. McEachron, TRANS. A. I. E. E., Vol. XLII, 1923, p. 947.

I believe it would be of value if Mr. Torok would give us the benefit of his ideas and experience with relation to the effect of the polarity of the sphere on the discharge so that his results may be correlated with the facts relating to 60-cycle discharges.

**J. J. Torok:** I wish to emphasize a few points that probably have not been made clear in my presentation.

Each photograph portrays the effects of a single surge on the apparatus under test. Mr. Peek and Mr. Eby have described tests in which they have made similar photographs of electrostatic fields. However, in their determinations, the voltage applied was always below breakdown value, and for that reason only the corona discharges were recorded. In our tests the voltage was raised well above the continuously applied breakdown potential and then was reduced to a negligible value before the developing streamers spanned the entire gap. This method has many advantages since it furnished: 1, a reliable determination of conditions throughout the entire field, 2, information on the process of breakdown at any stage of development, and 3, an indication of the process involved in the breakdown of air.

Mr. Duncan has suggested that the ionizing properties of ultra-violet light might be used as a basis for explaining this phenomenon. The ultra-violet light theory has been given consideration, but it seemed inapplicable in this case. The recombination of the free positive and negative ions liberates a given quantity of energy, only a part of which appears in the form of ultra-violet light. If all this energy were used in producing new electrons in the field (which is hardly possible), the maximum number of ions generated could not exceed the original number that had recombined. Thus from an energy standpoint, it is hard to justify this theory. Ultra-violet light may aid in the formation of the pink glow in the dark portions of the field, but the white streamers are probably formed by intensive thermal ionization, by which means a much greater proportion of electrons is produced than by ultra-violet light.

The time lags of sphere gaps and other apparatus can be attributed to the slowness of development of the white streamers. A study of the development of these streamers in various types of fields was made. It was found that the development depended upon the intensity of the field. In the near future some of these results as well as the methods by which they were obtained will be published.

Mr. Peek pointed out that his investigations showed that calculated waves checked very closely those recorded by the cathode-ray oscillograph. The surge-generator circuit used in producing these suppressed discharges contained many gaps which changed their resistances sufficiently on breakdown to modify the wave front. In some types of surge generators, there are fewer gaps, which reduces the arc-resistance variation.

As to the theory involved in the breakdown of air, the calculations that Dr. Slepian has made will probably eliminate many of the discrepancies and make it clearer than I could.

Regarding Mr. McEachron's question on polarization of the spheres, we are now working on this and it will be reported later.

# Approximate Solution for Electrical Networks
## When These are Highly Oscillatory

BY E. A. GUILLEMIN[1]
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***Synopsis.**—The general solution to the slightly damped network is expressed in terms of the undamped solution by means of series expansions. The first part of the paper gives a method for evaluating the complex roots of the determinantal equation, and the second part shows how the expansions of the first part may be correlated with the Heaviside formula to form the complete approximate solution. An example illustrates the application to a simple network.*

IN working out the general solution of an electrical network, subjected to suddenly applied e. m. fs., by the classical method, there are two steps which involve a disagreeable amount of calculation—the determination of the natural angular velocities of the system, and the evaluation of integration constants or transient current amplitudes. The use of Heaviside's expansion formula does considerable toward simplifying—at least systematizing—the latter; but there still remains the necessity of solving high powered algebraic equations, which, when the network contains more than two meshes, becomes a tedious process. Primary among the factors which contribute toward the unwieldiness of the solution are the dissipative terms introduced by the presence of ohmic resistances. The solution for an idealized system with no ohmic losses is much simpler both analytically and in consequent numerical manipulation. In the first place, the determinantal equation for this case contains only even powers of the independent variable, say $p$, and, when solved for $p^2$, contains only negative real roots which may be evaluated by Newton's or Lagrange's approximation methods when the degree is above the third in $p^2$. Secondly, only purely imaginary or purely real quantities enter into the manipulations involved in evaluating integration constants instead of complex quantities. As soon as resistance enters into the problem, and in actual cases it always does, the work increases manifold. In practise, however, it is very frequently the case that although resistances are present, they are very small and cause only a relatively slow attenuation. We call such circuits "highly oscillatory." Practically every network used in connection with radio telephony comes under this head. It would seem, therefore, both useful and very logical to approach this case from the standpoint of the perturbation problem, and consider the slightly damped network as perturbed out of its undamped condition. It is the object of this paper to show how, by means of expansion in series, this standpoint may be carried out. The same idea may be applied to the distributed constant problem and many others; and it is hoped that interest may be stimulated in this general direction.

If we consider the meshes in our electrical network numbered from 1 to $n$, and let $\lambda_{ii}, \rho_{ii}, \sigma_{ii}$ be the total inductance, resistance, and elastance, respectively, in mesh $i$, and further let $-\lambda_{ik}, -\rho_{ik}, -\sigma_{ik}$ be the total inductance, resistance, and elastance, respectively, common to meshes $i$ and $k$ ($\lambda_{ik}$ being the sum of mutual and common self inductances), then the system of homogeneous differential equations describing the natural mode of oscillation of the system, when written for the mesh charges, takes the form:[2]

$$\left.\begin{array}{l} a_{11}\,x_1 + a_{12}\,x_2 + \;.\;.\;.\;.\; + a_{1n}\,x_n = 0 \\ a_{21}\,x_1 + a_{22}\,x_2 + \;.\;.\;.\;.\; + a_{2n}\,x_n = 0 \\ .\;\;.\;\;.\;\;.\;\;.\;\;.\;\;.\;\;.\;\;.\;\;.\;\;.\;\;. \\ a_{n1}\,x_1 + a_{n2}\,x_2 + \;.\;.\;.\;.\; + a_{nn}\,x_n = 0 \end{array}\right\} \qquad (1)$$

$$\left.\begin{array}{ll} \text{with} & a_{ik} = \lambda_{ik}\dfrac{d^2}{d\,t^2} + \rho_{ik}\dfrac{d}{d\,t} + \sigma_{ik} \\ \text{and} & x_k = \displaystyle\int_0^t i_k\,d\,t \end{array}\right\} \qquad (2)$$

The use of mesh charges $x_k$ instead of mesh currents $i_k$ avoids the appearance of integrals in the system (1) and also brings out a closer analogy between the electrical system and the equivalent mechanical system in which displacements take the place of electrical charges. If we assume as solutions to system (1) the normal functions:

$$x_k = X_k\,\epsilon^{pt} \qquad (3)$$

there results the system of simultaneous homogeneous algebraic equations:

$$\left.\begin{array}{l} b_{11}\,X_1 + b_{12}\,X_2 + \;.\;.\;.\;.\; + b_{1n}\,X_n = 0 \\ b_{21}\,X_1 + b_{22}\,X_2 + \;.\;.\;.\;.\; + b_{2n}\,X_n = 0 \\ .\;\;.\;\;.\;\;.\;\;.\;\;.\;\;.\;\;.\;\;.\;\;.\;\;.\;\;. \\ b_{n1}\,X_1 + b_{n1}\,X_2 + \;.\;.\;.\;.\; + b_n\,X_n = 0 \end{array}\right\} \qquad (4)$$

$$\text{where:}\quad b_{ik} = b_{ik}\,(p) = \lambda_{ik}\,p^2 + \rho_{ik}\,p + \sigma_{ik} \qquad (5)$$

The assumptions (3) will be useful if system (4) leads to non-trivial solutions for the amplitudes $X_k$. This will be the case if the determinant of the system vanishes, *i. e.*, if:

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*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., February 13-17, 1928.*

[2] See Carson's "Electric Circuit Theory and Operational Calculus," McGraw-Hill, 1926. Our system of equations (1) is identical with Carson's system (14), p. 10, with the substitution: $i_k = \dfrac{d\,x_k}{d\,t}$, allowing for differences of notation, of course. Our following equations (4) and (6) correspond in the same way to Carson's equations (15) and (16), pp. 10 and 11

$$D(p) = \begin{vmatrix} b_{11} & \dots & b_{1n} \\ b_{21} & \dots & b_{2n} \\ \dots & \dots & \dots \\ b_{n1} & \dots & b_{nn} \end{vmatrix} = 0 \qquad (6)$$

For the solution to be unique it is further necessary that $D$ have the rank $n-1$, *i. e.*, that at least one of its first minors shall not vanish. Equation (**6**) is in compact form the determinantal equation of the oscillatory system. Since each element is in general a polynomial of the second degree in $p$, $D$ will be a polynomial of the $2\,n$th degree in $p$, and according to the fundamental law of algebra (**6**) can be satisfied in $2\,n$ ways. Hence $2\,n$ solutions (**3**) exist with $2\,n$ arbitrary amplitudes $X_k$ to satisfy the $2\,n$ initial charges and currents in the given electrical system.

Consistent with our major premise, we proceed to expand (**6**) in powers of $\rho_{ik}$ by Taylor's theorem. We have:[3]

$$D(p) = \Big[ D(p) \Big]_{\rho_{ik}=0} + \frac{1}{1\,!} \sum_{1}^{n}{}^{ik} \left[ \frac{\partial D(p)}{\partial \rho_{ik}} \right]_{\rho_{ik}=0} . \rho_{ik} + \dots \qquad (7)$$

But according to the rule for differentiating determinants:[4]

$$\frac{\partial D(p)}{\partial \rho_{ik}} = \frac{\partial D(p)}{\partial b_{ik}} \frac{\partial b_{ik}}{\partial \rho_{ik}} = B_{ik}(p) \frac{\partial b_{ik}}{\partial \rho_{ik}}$$
$$= B_{ik}(p) \, . \, p \qquad (8)$$

where $B_{ik}(p)$ is the minor of $b_{ik}$ in (**6**). Since $D(p)$ is a whole rational function in $\rho_{ik}$, the expansion (**7**) will contain a finite number of terms. From (**8**) it is evident[5] that successive terms will rapidly become smaller if $\rho_{ik} << p$. We will assume this and consequently neglect all powers of the $\rho_{ik}$'s above the first. If now we adopt the notation:

$$\left.\begin{aligned} \Big[ D(p) \Big]_{\rho_{ik}=0} &= D^*(p) \\ \text{and} \quad \Big[ B_{ik}(p) \Big]_{\rho_{ik}=0} &= B_{ik}{}^*(p) \end{aligned}\right\} \qquad (9)$$

our determinantal equation (**6**) becomes:

$$D(p) = D^*(p) + p \sum_{1}^{n}{}^{ik} B_{ik}{}^*(p) \, . \, \rho_{ik} = 0 \qquad (10)$$

A first approximation to the roots of (**10**) is given by:

$$D^*(p) = 0 \qquad (11)$$

which is the determinantal equation for neglected attenuation. As already pointed out, it contains only even powers of $p$, the roots for $p^2$ being negative real, and hence those for $p$ purely imaginary. Let the roots of (**11**) be given by:

$$p = p^* \qquad (12)$$

According to the Newtonian method[6] we then put for the roots of $D(p)$:

$$p = p^* + \delta \qquad (13)$$

and substitute this value into $D^*(p)$ of equation (**10**). For the second term in (**10**) it is sufficient to substitute (**12**). We then have:

$$D(p) = D^*(p^* + \delta) + p^* \sum_{1}^{n}{}^{ik} B_{ik}{}^*(p^*) \, . \, \rho_{ik} = 0 \qquad (14)$$

Expanding the first term in a Taylor's series about $p = p^*$ we get:

$$D^*(p^* + \delta) = D^*(p^*) + \frac{1}{1\,!} \left( \frac{\partial D^*}{\partial p} \right)_{p=p^*} . \, \delta + \dots \qquad (15)$$

Now if we note that

$$D^*(p) = C_n\, p^n + C_{n-2}\, p^{n-2} + \dots + C_0$$
$$= C_n\, (p^* + \delta)^n + C_{n-2}\, (p^* + \delta)^{n-2} + \dots + C_0$$

and $(p^* + \delta)^n$

$$= p^{*n} \left\{ 1 + \frac{n}{1\,!} \frac{\delta}{p^*} + \frac{n\,(n-1)}{2\,!} \left( \frac{\delta}{p^*} \right)^2 + \dots \right\}$$

we see that terms of (**15**) above the first degree in $\delta$ may be neglected if:

$$\frac{n-1}{2} \frac{\delta}{p^*} << 1 \qquad (16)$$

which is the criterion for a "highly oscillatory" network in the sense in which that term is used in this paper. Substituting (**15**) into (**14**) and noting that:

$$D^*(p^*) = 0,$$

and also that

$$\left[ \frac{\partial D^*}{\partial p} \right]_{p=p^*} = \sum_{1}^{n}{}^{ik} \left[ \frac{\partial D^*}{\partial b_{ik}} \frac{\partial b_{ik}}{\partial p} \right]_{p=p^*}$$
$$= \sum_{1}^{n}{}^{ik} 2\, \lambda_{ik}\, p^*\, B_{ik}{}^*(p^*) \qquad (17)$$

we get $\delta \sum^{n}{}^{ik} 2\, \lambda_{ik} B_{ik}{}^*(p^*) + \sum^{n}{}^{ik} \rho_{ik} B_{ik}{}^*(p^*) = 0$

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[3] See Wood's "Advanced Calculus," Ginn & Co., 1926, p. 49, equation (1), or any similar text covering Taylor's theorem.

[4] See, for example, R. F. Scott's "Theory of Determinants," Cambridge University Press, 1880, p. 35.

[5] This will be clear if we note that $B_{ik}$ is two powers lower in $p$ than $D$. Hence the second term of (**7**) divided by the first will be of the order: $\rho_{ik}/p$.

[6] See, for example, Woods & Bailey, "A Course in Mathematics," Ginn & Co., 1907, p. 114. The method is there shown applied to the solution of numerical equations, but the general idea involved is the same as that used in this paper.

$$\text{or } \delta = -\frac{\sum_{1}^{n}{}^{ik}\, \rho_{ik} B_{ik}^{*}(p^*)}{\sum_{1}^{n}{}^{ik}\, 2\,\lambda_{ik} B_{ik}^{*}(p^*)}. \tag{18}$$

From the form of (18) it is clear that $\delta$ will always be real, and hence represents the damping factor associated with the frequency given by $p^*$. The complete complex "natural angular velocity" so-called, is given by (13). The form of (18) is in itself interesting. The damping factors appear as the negative quotient of the averaged mesh resistances weighted by the unperturbed minors, and double the mesh inductances averaged in the same way. The dimension of $\delta$ and its similarity to that for the simple $R, L, C$ circuit are evident. The latter may serve as a simple illustration of our result. Here,

$$D(p) = b(p) = L p^2 + R p + \frac{1}{C} = 0.$$

$$D^*(p) = L p^2 + \frac{1}{C} = 0; \; p^* = \frac{\pm j}{\sqrt{LC}}.$$

The $B_{ik}^*$ are unity in this case and we have,

$$\delta = -\frac{R}{2L},$$

$$\text{and hence, } p = -\frac{R}{2L} \pm j \frac{1}{\sqrt{LC}}.$$

The exact root differs from this only in that the damped angular frequency,

$$\pm j \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

appears in place of the undamped.

Although equation (18) is applicable more directly to the mathematical representation of the network itself, the same idea can be carried out on the determinantal equation in its polynomial form. If we have given:

$$D(p) = A_n p^n + A_{n-1} p^{n-1} + \ldots + A_0 = 0 \tag{19}$$

it can easily be shown that the corresponding determinantal equation for the undamped case is approximately[7] given by simply striking the second, fourth, etc.. terms, *i. e.*, that:

$$D^*(p) = A_n p^n + A_{n-2} p^{n-2} + \ldots + A_0 = 0. \tag{20}$$

Then if we let,

$$G(p) = A_{n-1} p^{n-1} + A_{n-3} p^{n-3} + \ldots + A_1 p \tag{21}$$

$$\text{it will be seen that } \Big[ G(p) \Big]_{\rho_{ik}=0} = 0,$$

and hence that (21) can take the place of the double sum in (7). Applying the Newtonian method as before we find:

$$\delta = -\frac{G(p^*)}{\left(\frac{\partial D^*}{\partial p}\right)_{p=p^*}} \tag{22}$$

To illustrate the application of (22), let us consider the numerical quartic:

$$D(p) = p^4 + 50 p^3 + 8.91 \times 10^5 p^2 + 2.03 \cdot 10^7 p + 1.601 \cdot 10_n = 0$$

Here $D^*(p) = p^4 + 8.91 \cdot 10^5 p^2 + 1.601 \cdot 10^{11} = 0$

and $p^* = \pm j\,800$ and $\pm j\,500$.

For the first of these:

$$G(p^*) = \mp j\,9.36 \cdot 10^9; \left(\frac{\partial D^*}{\partial p}\right)_{p=p^*} = \mp j\,6.23 \cdot 10^8$$

and hence $\delta = -15.$

For the second:

$$G(p^*) = \pm j\,3.90 \cdot 10^9; \left(\frac{\partial D^*}{\partial p}\right)_{p=p^*} = \pm j\,3.90 \cdot 10^8,$$

and hence $\delta = -10.$

The final roots are:

$$-10 \pm j\,500 \text{ and } -15 \pm j\,800$$

which are exactly the ones used in making up the above equation, the differences due to the approximate method of solution not being noticeable on the slide rule used in the calculation.

It frequently happens that due to the absence of independent inductance or elastance in one of the meshes, the determinantal equation comes out to be of an odd degree. The number of natural angular frequencies contained in the system in that case will be $\frac{n-1}{2}$ where $n$ is the degree of the equation. The odd root will be purely real. The fact that it possesses a normal coordinate[8] as well as the rest of the frequencies but vanishes for vanishing resistances, seems to indicate physically that in the latter case a regrouping of the meshes can be carried out so as to reduce their number by one—there being always as many normal coordinates as there are meshes, (physical dimensions in the equivalent mechanical system). It would seem as though for this real root our method would fail, since its imaginary part is zero. However, it can be shown that so long as this real root is within the same order of magnitude as the real portions of the rest of the roots, the method still holds with fair accuracy. Let us suppose we have an equation of even degree given by:

$$D(p) = 0;$$

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[7] For the preceding simple example this happens to be exact; but in general the resistance terms will contribute a small ashre to the coefficients of even powers of $p$.

[8] See paper by the writer entitled "Making Normal Coordinates Coincide with the Meshes of an Electrical Network," *Proceedings* of the I. R. E., Nov. 1927, p. 935.

and we introduce an extra real root $p = -\alpha$. Then the equation of odd degree becomes:

$$D_0(p) = (p + \alpha)\, D(p) = 0. \tag{23}$$

The equation for neglected resistance would then be:

$$D_0^*(p) = p\, D^*(p) = 0,$$

which contains the zero root mentioned above. Hence, substituting $p = 0 + \delta$ into (**23**) and expanding we get:

$$D_0(\delta) = D_0(0) + \frac{1}{1!}\left(\frac{\partial D_0}{\partial p}\right)_{p=0} \ldots + \ldots = 0,$$

$$\text{and} \quad \delta = -\frac{D_0(0)}{\left(\dfrac{\partial D_0}{\partial p}\right)_{p=0}}.$$

But: $\quad D_0(0) = \alpha\, D(0),$

$$\text{and} \quad \left(\frac{\partial D_0}{\partial p}\right)_{p=0} = \alpha\left(\frac{\partial D}{\partial p}\right)_{p=0} + D(0),$$

$$\text{so that:} \quad \delta = -\frac{\alpha\, D(0)}{D(0) + \alpha\left(\dfrac{\partial D}{\partial p}\right)_{p=0}},$$

from which it is clear that the method still gives satisfactory results if:

$$\alpha\left(\frac{\partial D}{\partial p}\right)_{p=0.} < < D(0);$$

or by using the notation of equation (**19**), if:

$$\alpha < < \frac{a_0}{a_1}.$$

In our numerical example above, this means that an additional real root $(p + \alpha)$ may be introduced and re-evaluated by formula (**22**) with good results as long as

$$\alpha < < \frac{1.601 \cdot 10^{11}}{2.03 \cdot 10^{7}} = 7890,$$

which condition is easily fulfilled if $\alpha$ is not much larger than the real portions of the other roots. Note that for the evaluation of this real root equation (**22**) simply becomes equal to the negative quotient of the last two coefficients of the odd powered determinantal equation in the form of (**19**). After this odd root has thus been determined, it is best to divide it out and then treat the remainder as in the case where $D(p)$ is of even degree. To illustrate let us take our previous numerical example, and introduce the root $p = -100$. It then becomes:

$$D(p) = p^5 + 150\, p^4 + 8.96 \cdot 10^5\, p^3 + 1.094 \cdot 10^8\, p^2 + 1.62 \cdot 10^{11}\, p + 1.601 \cdot 10^{13} = 0.$$

Here: $\quad D^*(p) = p^5 + 8.96 \cdot 10^5\, p^3 + 1.62 \cdot 10^{11}\, p,$

and $\quad G(p) = 150\, p^4 + 1.094 \cdot 10^8\, p^2 + 1.601 \cdot 10^{13}.$

By applying (**22**) for $p^* = 0$ we get:

$$\delta = -\frac{1.601 \cdot 10^{13}}{1.62 \cdot 10^{11}} = -98.8$$

which is the root correct to within 0.2 per cent.

Our next step is to show how nicely the above method of arriving at the approximate complex roots fits in with an approximate determination of the transient current amplitudes by means of Heaviside's well-known expansion formula. The latter may be put into the form:[9]

$$i_{ik} = E \sum\nolimits^{\nu} \frac{B_{ik}(p_\nu)\, \epsilon^{p\nu t}}{\left(\dfrac{\partial D}{\partial p}\right)_{p=p\nu^*}} \tag{24}$$

when written for the current in mesh $i$ due to a suddenly applied direct voltage $E$ in mesh $k$ or vice versa. $D(p)$ is the determinant given by (**6**), and $B_{ik}$ the respective minor of this determinant. The summation is to extend over all the roots of the determinantal equation:

$$D(p) = 0.$$

For the case of slight damping, however, the solution is given approximately by:

$$i_{ik} = E \sum\nolimits^{\nu} \frac{B_{ik}^*(p_\nu^*)\, \epsilon^{p\nu t}}{\left(\dfrac{\partial D^*}{\partial p}\right)_{p=p\nu^*}}. \tag{25}$$

But the denominators in this sum are already known from equation (**17**), so that we merely have to substitute these same values into (**25**) in order to get the complete solution. The approximate solution to the determinantal equation dovetails nicely with the process of evaluation of the transient current amplitudes. Substituting (**17**) into (**25**), we can write for Heaviside's expansion formula in approximate form:

$$i_{ik} = \frac{E}{2} \sum\nolimits^{\nu} \frac{B_{ik}^*(p_\nu^*)\, \epsilon^{p\nu}{}_{t}}{p_\nu^* \displaystyle\sum_{1}^{n}{}^{ik} \lambda_{ik}\, B_{ik}^*(p_\nu^*)} \tag{26}$$

If the determinantal equation (**6**) has no zero root, it means that the mesh in which the e. m. f. is impressed contains a condenser so that the steady state becomes

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[9] It will be seen with a little investigation that our:

$$\frac{D(p)}{B(p)} = p\, Z(p)$$

where $Z(p)$ is the transient impedance as usually defined in connection with Heaviside's expansion formula. Now:

$$\frac{d}{dp}\left[\frac{D}{B}\right]_{p=p\nu} = \left[\frac{B \cdot \dfrac{dD}{dp} - D\dfrac{dB}{dp}}{B^2}\right]_{p=p\nu} = \frac{\left(\dfrac{dD}{dp}\right)_{p=p\nu}}{B(p^\nu)}$$

$$= \left[p\frac{dZ}{dp} + Z\right]_{p=p\nu} = p^\nu \left(\frac{dZ}{dp}\right)_{p=p\nu} + Z(p^\nu).$$

Comparing with the usual form of Heaviside's formula, the form (**24**) will be seen to be identical with it. For additional information on this point, see "Notes on Operational Calculus," by V. Bush, obtainable from the Electrical Engineering Dept. of the Massachusetts Institute of Technology, Cambridge, Mass.

zero. Since the terms in (**26**) are conjugate pairs, the current will be twice the real portion, or:

$$i_{ik} = E \sum_{1,3,5..}^{n} {}^{\nu} \frac{B_{ik}{}^{*}(p_\nu{}^{*})\,\epsilon^{\delta t}}{|\,p_\nu{}^{*}\,| \sum_{1}^{n} {}^{ik} \lambda_{ik} B_{ik}{}^{*}(p_\nu{}^{*})} \sin |\,p_\nu{}^{*} I t\,| \quad (27)$$

In order to illustrate the entire process of solution outlined in this paper, let us consider a simple network consisting of two inductively coupled meshes with a suddenly applied constant potential of $E$ volts in the first,—the circuit constants being given by:

$\lambda_{11} = 0.3$ henries; $\lambda_{12} = -.1$ henries; $\lambda_{22} = 0.2$ henries.
$\rho_{11} = 5$ ohms; $\rho_{12} = 0$; $\rho_{22} = 5$ ohms.
$\sigma_{11} = 10^6$ darafs; $\sigma_{12} = 0$; $\sigma_{22} = 10^8$ darafs.

Then,

$$D^{*}(p) = \begin{vmatrix} .3\,p^2 + 10^6 & -.1\,p^2 \\ -.1\,p^2 & .2\,p^2 + 10^8 \end{vmatrix}$$

$$= p^4 + 6.04 \cdot 10^8\,p^2 + 2 \cdot 10^{15} = 0.$$

From which $p_{1,2}{}^{*} = \pm j\,2.45 \cdot 10^4$; $p_{3,4}{}^{*} = \pm j\,1.87 \cdot 10^3$.

We then find

$B_{11}{}^{*}(p_{1,2}{}^{*}) = -2 \cdot 10^7$; $B_{12}{}^{*}(p_{1,2}{}^{*}) = -6 \cdot 10^7$; $B_{22}{}^{*}(p_{1,2}{}^{*}) = -1.79 \cdot 10^8$.

and $B_{11}{}^{*}(p_{3,4}{}^{*}) = 9.93 \cdot 10^7$; $B_{12}{}^{*}(p_{3,4}{}^{*}) = -3.5 \cdot 10^5$; $B_{22}{}^{*}(p_{3,4}{}^{*}) = -5 \cdot 10^4$.

From which $\sum_{1}^{n} {}^{ik} \rho_{ik} B_{ik}{}^{*}(p_{1,2}{}^{*}) = -9.95 \cdot 10^8$;

$$\sum_{1}^{n} {}^{ik} \rho_{ik} B_{ik}{}^{*}(p_{3,4}{}^{*}) = 4.965 \cdot 10^8,$$

and $\sum_{1}^{n} {}^{ik} 2\,\lambda_{ik} B_{ik}{}^{*}(p_{1,2}{}^{*}) = -5.96 \cdot 10^7$;

$$\sum_{1}^{n} {}^{ik} 2\,\lambda_{ik} B_{ik}{}^{*}(p_{3,4}{}^{*}) = 5.97 \cdot 10^7.$$

and substituting into (**18**) we have:

$$\delta_{1,2} = -\frac{9.95 \cdot 10^8}{5.96 \cdot 10^7} = -16.7$$

$$\delta_{3,4} = -\frac{4.96 \cdot 10}{5.97 \cdot 10^7} = -8.33$$

Then substituting into (**27**) we get for the current in mesh one:

$$i_{11} = E\,(2.74 \cdot 10^{-5}\,\epsilon^{-16.7t} \sin 24500\,t + 1.78 \cdot 10^{-3}\,\epsilon^{-8.33t} \sin 1870\,t).$$

The current in mesh two is found from this by simply multiplying the first term by $\frac{B_{12}{}^{*}(p_{1,2}{}^{*})}{B_{11}{}^{*}(p_{1,2}{}^{*})}$,

and the second by $\frac{B_{12}{}^{*}(p_{3,4}{}^{*})}{B_{11}{}^{*}(p_{3,4}{}^{*})}$.

We find $i_{12} = E\,(8.22 \cdot 10^{-5}\,\epsilon^{-16.7t} \sin 24500\,t - 6.28 \cdot 10^{-6}\,\epsilon^{-8.33t} \sin 1870\,t)$.

It is quite apparent that the saving in tedious manipulation over the usual method is considerable.

## Discussion

**V. Bush:** Unfortunately, every time we try to apply Heaviside's expansion theorem to any network of moderate complication we run into insurmountable difficulties in computation. Those appear specifically in an equation of a higher order which we must solve for the roots. Dr. Guillemin has shown us how in general, in any case where the dissipation is small, we can arrive at those roots and at a form of the expansion theorem which is sufficiently accurate by methods which are much shorter than the complete methods. The object is the exposition of modified forms of treatment for oscillatory cases of low damping.

**E. A. Guillemin:** There is an additional point in connection with the approximate method of solution, which was not mentioned explicitly in the paper, but which may be of interest to those who wish to apply it to specific problems.

Two methods of attack for the evaluation of the complex roots were presented: The first was based upon the determinantal equation in its determinant form (Equation **6**), and the second, upon the determinantal equation in its polynominal form (Equation **19**). The correlation of this process of evaluation of roots with the Heaviside formula (Equation **25**), however, was carried through only on the determinant basis, and brought into the explicit form given by Equation **27**. The same correlation may, of course, be carried through in connection with the determinantal equation in its polynomial form, as follows:

Equation **22** may be solved for $\left(\frac{\partial D^{*}}{\partial p}\right) p = p^{*}$ and the result substituted in Equation **25**. Grouping pairs of conjugate terms, the final result is:

$$i_{in} = -2\,E \sum_{1,3,5}^{n} {}^{\nu} \frac{\delta_\nu B_{in}{}^{*}(p^{*}{}_\nu)\,.\,\epsilon^{\delta_\nu t}}{|\,G\,(p^{*}{}_\nu)\,|} \sin |\,p_\nu{}^{*}|\,t\,.$$

On applying this form it should be noted that $G\,(p^{*}{}_\nu)$ is a purely imaginary quantity and of the form $\pm j$ times an absolute magnitude which may be numerically positive or negative in itself. It is this numerical quantity (with proper sign) which is to be substituted in the above formula.

# The Boltzmann-Hopkinson Principle
## of Superposition as Applied to Dielectrics

BY F. D. MURNAGHAN[1]
Non-member

***Synopsis.**—The principle of superposition, discussed first for dielectrics by Hopkinson, has been shown for a long time in experiment. However, its validity for the several theories which have been advanced for dielectric behavior has been shown in only a few cases. One of the exceptions is the important theory of Maxwell.*[2] *This paper shows that the principle of superposition is a necessary consequence of Maxwell's theory. It goes somewhat further and shows that the principle is valid for any theory which leads to a system of linear differential equations with constant coefficients.*

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If we have a plane layer dielectric with $n$ layers and denote the thickness of the $r$th layer by $a_r$, its specific inductive capacity by $K_r$, and its specific resistance by $r_r$ then the common current density $u$ in each layer is given by

$$u = (D + b_r) f_r \qquad (1)$$

when $D$ denotes time differentiation,[3] $f_r$ stands for the displacement in the $r$th layer, and $b_r$ is an abbreviation for the ratio $4\,\pi / K_r\, r_r$. Furthermore, the displacements $f$ are connected with the applied e. m. f. $E$ by the equation

$$\alpha_1 f_1 + \alpha_2 f_2 + \ldots + \alpha_n f_n = E \qquad (2)$$

where $\alpha_r$ is an abbreviation for the ratio $4\,\pi\, a_r / K_r$. These equations lead to a linear differential equation of order $n - 1$ for each of the displacements $f$, the equation satisfied by $f_r$, being

$$\left[\frac{\alpha_1}{D + b_1} + \frac{\alpha_2}{D + b_2} \cdots + \frac{\alpha_n}{D + b_n}\right] f_r = \frac{E}{D + b_r} \qquad (3)$$

it being understood, however, that this is merely a convenient way of writing the differential equation which results when both sides are cleared of fractions by multiplying through by the product of all the denominators $(D + b_r)$. The dielectric being supposed initially uncharged we have to find solutions of (3), consistent with (1), which have all the same value $E(0)/\alpha_1 + \ldots + \alpha_n)$ when $t = 0$.

The differential equation (3) has on the left hand side a differential expression $F(D)$ of order $n - 1$, the coefficient of the highest order derivative $D^{n-1}$ being $(\alpha_1 + \alpha_2 + \ldots + \alpha_n)$, and we shall denote this coefficient by $A$, for convenience. The right hand side of (3) is the result of differentiating the function $E$ of $t$ in the manner indicated by the product of all the $(D + b)$ save the single one $(D + b_r)$. It will be convenient first to consider the auxiliary equation

$$F(D)\, y = E(t) \qquad (4)$$

since if we have a solution $y$ of this equation the function $f_r$ obtained by operating on $y$ by the product of all the $(D + b)$ save the single one $(D + b_r)$ will satisfy the equation (3). In fact since the coefficients in the polynominal $F(D)$ are constants we may interchange the order of the differentiations indicated by $F(D)$ and by the product of the factors $(D + b)$. Hence

$$\begin{aligned} F(D)\ .\ (D + b_1)(\ .\ .\ .\ )(D + b_n)\, y &= (D + b_1)(\ .\ .\ .\ )(D + b_n)\ .\ F(D)\, y \\ &= (D + b_1)(\ .\ .\ .\ )(D + b_n)\, E(t) \end{aligned}$$

We now proceed to find, by a method due to Cauchy, that particular solution of the equation (4) which vanishes, together with all its derivatives up to the $n - 2$nd inclusive when $t = 0$. The homogeneous equation corresponding to (4), *i. e.*,

$$F(D)\, z = 0 \qquad (5)$$

being of order $n - 1$, has $n - 1$ distinct solutions which we may denote by $(z_1, z_2, \ldots z_{n-1})$, and the general solution of (5) is, in accordance with the theory of linear differential equations, a combination, with constant coefficients, of these $n$ distinct solutions. Thus the general solution of (5) may be written in the form

$$z = C_1 z_1 + C_2 z_2 + \ldots + C_{n-1} z_{n-1} \qquad (6)$$

The constants $C$ are entirely arbitrary and we choose them so that the function $z$ of $t$ defined by (6) vanishes together with its derivatives up to the $n - 3$rd inclusive when $t = \tau$; the $n - 2$nd derivative, on the contrary, assuming the value $E(\tau)/A$. The prescribing of the values of $z$ and its derivatives up to the $n - 2$nd, inclusive, in this way for a particular value $\tau$ of $t$ gives us exactly $n - 1$ linear equations for the determination of the values of the constants $C$ which occur in (6). These constants will depend on the particular value $\tau$ of $t$ chosen to enable us to determine them by means of the conditions stated and they will, in addition, be proportional to $E(\tau)$ since the right hand members of the $n - 1$ linear equations for the $C$'s are all zero save one which is precisely $E(\tau)/A$. We shall indicate these facts by writing $z$ of (6) in the form

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[1] Johns Hopkins University.

[2] See Maxwell's Theory of the Layer Dielectric, F. D. Murnaghan, TRANS. A. I. E. E., Vol. XLVI, 1927, p. 259.

[3] The symbol $D$ stands for $d/d\,t$ and is used throughout the paper symbolically as an algebraic quantity. For the use of the symbolic operator $D + b$ in the solution of linear differential equations with constant coefficients see any standard treatise on the subject, for example, Cohen's Differential Equations (Heath & Co), p. 96.

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$$z = E(\tau)\, v(t, \tau) \qquad (7)$$

The fact that the coefficients in the differential operator $F(D)$ of (**5**) are constants tells us further that the function $v$ of the two arguments $t$ and $\tau$ does not really involve them separately but is rather a function of their difference $(t - \tau)$. In fact the functions $z_1$, etc., are exponential functions of the time and these exponential functions reproduce themselves, multiplied by a constant factor, when differentiated with respect to the time. Hence each $C$ occurs, in the $n - 1$ linear equations which serve to determine them, multiplied by the same factor $e^{\delta_r \tau}$, say, in each of the equations. This tells us that the $v(t, \tau)$ of (**7**) is of the type

$$v(t, \tau) = B_1\, e^{\delta_1 (t-\tau)} + \ldots + B_{n-1}\, e^{\delta_{n-1} (t-\tau)} \qquad (8)$$

where the $B$'s are pure numbers independent of both $t$ and $\tau$. The $\delta$'s are the zeros of the polynominal $F(D)$. We have found, then, a function

$$z = E(\tau)\, .\, v(t - \tau) \qquad (9)$$

which satisfies the homogeneous equation (**5**) and which vanishes together with its derivatives with respect to $t$ up to the $n-$ 3rd inclusive when $t = \tau$ (*i. e.*, when the argument $t - \tau$ of the function $v$ is zero); the $n-$ 2nd derivative assuming the value $E(\tau)/A$ when the argument of $v$ is zero. We now proceed to show that the function $y$ of the single variable $t$, defined by the integral

$$y = \int_0^t E(\tau)\, .\, v(t - \tau)\, d\tau \qquad (10)$$

is that particular solution of the equation (**4**) which vanishes together with its time derivatives up to the $n-$ 2nd, inclusive, when $t = 0$; in fact, since the variable $t$ occurs in two places—the integrand and the upper limit—in the expression for $y$ we have for the time derivative of $y$

$$D y = \int_0^t E(\tau)\, .\, D v(t - \tau)\, d\tau + E(t)\, .\, v(0)$$

The second member on the right hand side vanishes, since the function $v$ has been so arranged as to vanish when its argument is zero. Proceeding to the second time derivative we find in the same way that

$$D^2 y = \int_0^t E(\tau)\, .\, D^2 v(t - \tau)\, d\tau$$

and so on up to the $n-$ 1st time derivative, which is slightly different; here the second term in the expression for the time derivative of the integral does not vanish, since the $n-$ 2nd time derivative of $v$ does not vanish when the argument of $v$ is zero but has the value $1/A$ then. We have, therefore,

$$D^{n-1} y = \int_0^t E(\tau)\, .\, D^{n-1} v(t - \tau)\, d\tau + E(t)/A$$

Upon combining these results and remembering that the coefficient of the highest order derivative, $D^{n-1}$, in $F(D)$ is $A$, we have

$$F(D)\, y = \int_0^t E(\tau)\, .\, F(D)\, v(t - \tau)\, d\tau + E(t)$$

The first member of the expression on the right vanishes since the function $v$ of $t$ is a solution of the homogeneous equation (**5**), *i. e.*, $F(D)\, v(t - \tau) = 0$ for all values of the argument $(t - \tau)$. This shows that $y$, as defined by (**10**) is a solution of (**4**), and since all the derivatives up to the $n-$ 2nd, inclusive, are expressed as integrals, the range of integration being from zero to $t$, all of these derivatives and the function $y$ itself vanish when $t = 0$.

The various displacements $f_r$ are now obtained from the auxiliary function $y$ by operating on it in turn by the product of all the $(D + b)$'s but the single one $(D + b_r)$. From the expressions just given for the various time derivatives of $y$ up to the $n-$ 1st we have, for example,

$$f_1 = \int_0^t E(\tau)\, .\, (D + b_2)(.\ \ .\ \ .)(D + b_n)\, v(t - \tau)\, d\tau$$
$$+ E(t)/A \qquad (11)$$

showing that the common initial value of all the displacements is $E(0)/A$. It will be convenient to introduce the notation

$$h_1(t - \tau) = (D + b_2)(.\ \ .\ \ .)(D + b_n)\, v(t - \tau) \qquad (12)$$

etc., the function $h_r(t - \tau)$ being the result of operating on the function $v(t - \tau)$ by the product of all the $(D + b)$'s but $(D + b_r)$. We have, then, the various displacements given by the formulas

$$f_r = \int_0^t E(\tau) \quad h_r(t - \tau)\, d\tau + E(t)/A \qquad (13)$$

The $n$ functions $h_r$ all have the same value $1/A$ when the argument $(t - \tau)$ is zero. The formulas (**13**) become more significant, from a physical point of view, if we change their appearance by an integration by parts. On introducing the functions $\varphi_r(t - \tau)$ by the equations of definition

$$\varphi_r(t - \tau) = \int_\tau^t h_r(t - s)\, ds + 1/A \qquad (14)$$

so that

$$\frac{d}{d\tau}\, \varphi_r(t - \tau) = -\, h_r(t - \tau)$$

we have from (**13**)

$$f_r = E(0)\, \varphi_r(t) - E(t)\, \varphi_r(0)$$
$$+ \int_0^t \frac{dE}{d\tau}\, \varphi_r(t - \tau)\, d\tau + E(t)/A$$

The second term in the expression on the right hand cancels the fourth, since when the argument of $\varphi_r$ is zero, the two limits of the integral of (**14**) coincide so that $\varphi_r(0) = 1/A$. Then we have the final definite result

$$f_r = E\,(0)\,\varphi_r\,(t) + \int_0^t \frac{d\,E}{d\,\tau}\,\varphi_r\,(t-\tau)\,d\,\tau \qquad (15)$$

This equation gives a physical interpretation to the functions $\varphi$; for, on writing $E\,(t) = 1$ in (**15**), we see that $\varphi_r\,(t)$ is the displacement in the $r$th layer when a constant unit e. m. f. is applied at time $t = 0$ to the dielectric supposed uncharged.

The result given in (**15**) is the mathematical expression of the Boltzmann-Hopkinson Principle of Superposition as applied to the displacements. It is evident from its mode that the principle of superposition is valid not only for Maxwell's theory of dielectric absorption but for any theory which leads to a system of differential equations which are linear and have constant coefficients. For example a theory in which the current density was connected with the displacement by a second order equation of the type $(D^2 + b_r\,D + c_r)\,f_r = u$ would have the principle of superposition as a consequence.

Once the displacements have been found the current density $u$ follows at once from (**1**). Writing

$$\psi\,(t-\tau) = (D + b_r)\,\varphi_r\,(t-\tau) \qquad (16)$$

(it is easily verified that the expression on the right has the same value for all the layers) we find

$$u\,(t) = E\,(0)\,\psi\,(t) + \int_0^t \frac{d\,E}{d\,\tau}\,\psi\,(t-\tau)\,d\,\tau + \frac{d\,E}{d\,t}\bigg|\,A \qquad (17)$$

The physical meaning of the function $\psi\,(t)$ is evident from this formula; it is the current at time $t$ due to a constant unit e. m. f. applied to the uncharged dielectric at time $t = 0$. The principle of superposition is not valid for the entire current but the first two terms of (**17**) may be found by means of that principal and then the complete current follows by adding the displacement current which is given by the third term.

We have given elsewhere[4] the expression for the function $\psi$ in terms of the constants of the layer dielectric and the formula (**17**) furnishes a ready method for calculating the current due to any type of applied e. m. f.

## Discussion

**J. B. Whitehead:** (by letter) Most electrical engineers who are concerned with the behavior of dielectrics and insulation are aware that Maxwell's theory of dielectric absorption or residual charge cannot be applied for the predetermination of the properties of composite dielectrics and insulation. Yet Maxwell's theory is the only rational theory which has been proposed in this field, and the only one which seems to offer the possibility of experimental verification. Furthermore, the present indifference on the part of physicists to this important and highly interesting phenomenon is explained in many instances by their feeling that Maxwell has given a sufficient explanation.

The Committee on Electrical Insulation of the National Research Council several years ago set for itself the task of reviewing, collecting, and coordinating the existing knowledge as to the various properties of dielectrics. In considering Maxwell's theory it was realized that in several particulars it was incomplete as originally presented by the author. Among the most important of these was the absence of the complete expression for the charging current in the most general case of $n$ layers, and the absence of a formal statement or proof that the Boltzmann-Hopkinson principle of superposition was a necessary consequence of Maxwell's theory of dielectric absorption. On the first of these questions Maxwell contented himself with a general statement, and he doubtless was convinced of the certainty of the second, because he was intimately acquainted with Hopkinson's work and indeed discussed with him the experimental evidence of the presence of the principle of superposition in Hopkinson's experiments on dielectrics. Responding to questions on the mathematical aspects of these problems, Dr. Murnaghan was kind enough to become deeply interested in them and has given us his paper[1] of last year, clearing up the first of the problems mentioned above. He now presents a second paper analyzing the relationship of superposition and Maxwell's theory of dielectric absorption. As will be clear in the concluding paragraphs of the paper, it is shown that the principle of superposition is valid for the displacements in a layer dielectric, but not for the total current. The final term in Equation **17**, indicating the important addition, might be called the variation of the average geometrical displacement.

Whatever may be said as to the difficulties encountered in an effort to apply Maxwell's theory, Dr. Murnaghan's two papers constitute important commentaries on the theory, and will be of great assistance to all students in rounding out the picture conceived by Maxwell.

**V. Bush:** I have found it difficult indeed to get at the point of this paper, and hence I should like to give my interpretation of it in engineering language.

In applying the Boltzmann-Hopkinson extension theorem, or the superposition principle, we are passing from the d-c. transient of a network to the a-c. transient, or, more generally, we are passing from the response to a unit e. m. f. to the response to any applied voltage whatever. This can be done whenever the network is linear, that is, where the effect of two volts is exactly twice the effect of one volt. If we cannot thus superpose results we cannot use the superposition principle, and the reverse is also true. Now, as far as this is concerned with dielectrics it doesn't lead us very far, because in the most interesting cases results do not add simply. If we assume Maxwell's theory of dielectrics, they do; but unfortunately practical dielectrics do not work that way. I see, however, in Dr. Murnaghan's paper a matter of more general interest than this and which I do not think he brought out so that it is immediately apparent. There is difficulty in applying the superposition principle even in certain linear circuits. Sometimes the response to a unit applied e. m. f. is impulsive. If we suddenly apply a unit e. m. f. to a simple condenser the current is impulsive; that is, it is mathematically infinite and lasts for an infinitesimal time. In such a case it is difficult to apply the principle and we require some further treatment. Such networks are of course only mathematical fictions, as there is always in practical cases some series resistance present in the circuit or the source. Wherever such difficulties are encountered we can use the last equation in Dr. Murnaghan's paper and arrive at a result. An engineering way of doing the same thing is to insert a small series resistance to make the circuit behave normally. That will always avoid impulsive response.

But if we wish to treat the simpler circuit, and without thus avoiding the discontinuity, we can do it in the way there suggested, which in brief is this: We apply the superposition principle using the response to the unit e. m. f. ignoring the sudden impulse, and then we add on another term which takes account of the effect of the impulsive part.

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[4] A. I. E. E. Journal, February 1927 p. 132.

[1] *Maxwell's Theory of the Layer Dielectrics*, F. D. Murnaghan, Trans. A. I. E. E., Vol. XLVI, 1927, p. 259.

The superposition principle has been often treated in Institute papers, and the mathematical use of it is extensive. I should like to refer to the 1926 paper of Vladimir Karapetoff, and of J. B. Whitehead, and particularly to the discussion of those papers by Joseph Slepian; and I should like more especially to refer to the work of J. R. Carson in a number of papers where he has treated this matter in condiderable detail. Carson's proofs and modified forms furnish, in my opinion, an excellent and complete guide to its validity and use.

**E R. LeGhait:** One reason why the subject treated by Mr. Murnaghan is of a great practical interest is because the equation expressing the principle of superposition offers a ready means for finding the relationship between the absorption and the a-c. losses of a dielectric.

For instance if in Equation 17 of Mr. Murnaghan's paper, the memory function $\psi(t)$ has been determined by absorption measurements and if one expresses that $E$ is an alternating electromotive force of a certain frequency one is able to deduce therefrom the losses and dielectric power factor at that frequency. One sees at the same time the influence of the nature of the memory function on the shape of the power-factor frequency curve and one grasps very clearly the fact that absorption and a-c. losses are nothing but two different aspects of the same underlying phenomenon.

Moreover the following fact is put in evidence, namely that for any dielectric following the principle of superposition the a-c. losses vary as the square of the voltage. This means that for such a dielectric the power factor is independent of voltage.

In practise the power factor has been found to remain constant with voltage for all substances for which the principle of superposition was found to hold and in general for most solid dielectrics, at least when the conditions of test are such that no secondary phenomena are involved.

In the case of non-impregnated paper we were able to check experimentally the relationship between absorption and a-c. losses derived theoretically from the expression of the principle of superposition. This was found possible provided the memory function $\psi(t)$ is well determined experimentally for the values of $t$ that are of the order of magnitude of the duration of a cycle of the alternating current for which the losses are measured.

For complete dielectrics like oil-impregnated paper the conditions are very different. It is well known that the anomalous absorption current in liquid dielectrics does not follow the principle of superposition. In correlation with this the power factor of oil-impregnated paper even, and especially at very low stresses, does not remain constant with voltage. It varies widely on the contrary and its variations are markedly affected by frequency and temperatures.

In this case we have not at our disposal the so convenient expression of the principle of superposition and it is very difficult to find a relation between absorption and a-c. losses. This has however been done to some extent qualitatively at least. Moreover the cause of the variations of power factor with voltages has been traced back to the fact that the anomalous currents in the minute particles of oil present in the insulation do not follow the principle of superposition.

We believe that a close study of the phenomena presented by composite dielectrics that are in contradiction with the principle of superposition is capable of throwing new light on the mechanism of losses in that type of insulation and of determining the part played in their formation by the different elements entering in its constitution.

**M. G. Malti:** Since no physical statement of the Boltzmann-Hopkinson principle of superposition is given in Dr. Murnaghan's paper, I should like to supply a statement of this principle and then show that it holds true within a very limited range of potential.

Let three condensers $A$, $B$, and $C$, be identical in every respect as to the thickness and material of dielectric, as well as to the area and material of plates. Let continuous potentials $E_a$, $E_b$, and $E_c$ be applied to condensers $A$, $B$, and $C$ respectively such that $E_a = E_b + E_c$ and let the charges $Q_a$, $Q_b$, and $Q_c$, acquired by these condensers, be determined as defined by the writer.[2] The principle of superposition states that, under these conditions, $Q_a = Q_b + Q_c$.

This principle assumes a linear relation between $Q$ and $E$ as shown by ($a$) in Fig. 1 herewith. As a matter of fact the relation is linear only up to a certain value $E_a$ of the applied potential. For values higher than $E_a$ the relation follows the curve $b$.[3]

While Dr. Murnaghan's paper is a fine piece of mathematical work its utility is limited to potentials lying within the initial potential range $o - E_a$ because the principle of superposition fails beyond this range.

**Joseph Slepian:** It has always seemed to me that undue prominence has been given to the Maxwell multi-layer theory of dielectrics. It is true that a dielectric built up of layers, as Maxwell postulates, will show the phenomenon of absorption and that by using enough layers an absorption curve may be obtained which will approach as near as is desired to actual observed absorption curves. But it does not follow that if a dielectric shows an absorption curve it must be built of layers.

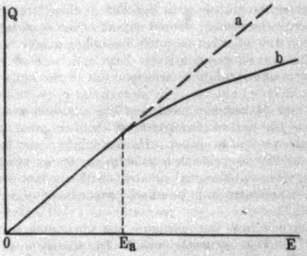

FIG. 1—RELATION BETWEEN CHARGE AND VOLTAGE IN SOLID DIELECTRICS

The situation is something like this: Given a box with a pair of terminals which when measured from the terminals acts as if it contained a resistor whether the measurements are made with continuous current, or with transients of the most varied sort. Can we then conclude that there is a resistor in the box? Clearly not. Networks can be set up in many ways which will perfectly imitate a resistor if measurements are confined to the terminals, as for example, in Figs. 2 and 3 shown herewith. So far as the terminals go these two circuits act exactly like ohmic resistors.

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[2] See Eq. (9) in *A Theory of Imperfect Solid Dielectrics*, by M. G. Malti, TRANS. A. I. E. E., Vol. XLVI, 1927, p. 616

[3] Ibid. bibliography Nos. 54-21, 109-21, 107-24 and the following:

3/93 "Hysteresis and Viscosity of Mica for Rapid Oscillations," P. Janet. C. R. Vol. 116, p. 373, 1893. *J de Phys*. 3, 2, p. 337, 1893.

34/95 "On the Question of Dielectric Hysteresis," A. W. Potter and D. K. Morris. *Proc. Roy. Soc.* 57, p. 469, 1895.

35/95 "Energy Loss in Dielectrics," P. Granier, *Electrician* 36, p. 7. 1895.

18/97 "Conversion of Electrical Energy in Dielectrics," R. Threlfall. *Phys. Rev.* 4, p. 457 and 5 p. 21, 65, 1897.

52/04 and 53/04 "Solid Dielectrics," V. Crémieu and L. Malcles C. R. 139, p. 790 and 969, 1904.

60/11 "Measurement of Losses in Fibrous Dielectrics," H. Jordan. *Elek. Zeits.*, Vol. 32, p. 127, 1911.

8/14 "Passage of Electricity through Paraffin," G. G. deVillemontée, C. R. 158, pp. 1414, and 1571. 1914.

102/21 "Viscosity of Dielectrics," J. Granier, *Rev. Gen. de Elec.* Vol. 10, p. 219, 1921.

13/23 "Reversible Inductivity of Rochelle Salt Crystals," J. G. Frayne, *Phys. Rev.* 21, p. 348, 1923.

No amount of mathematical manipulation of the terminal quantities is ever going to give exact information as to what is inside the box. The obvious thing to do is to get into the box, open it up, and examine what is going on there.

In my discussion of Dr. Murnaghan's paper of a year ago I mentioned, in this connection, the work of the Russian, Joffe, who was actually getting into the box, but probing the interior of insulation under stress. If we can't get into the box, then the thing to do is to find the conditions where the simple Ohm's Law fails in some way. In the case of the network shown in Fig. 2, by going to such voltages that the condenser breaks down something will be learned of the network structure. In the case of the transmission line Fig. 3, the current might be raised until the resistor burned out, and then by examining the characteristics of what was left something might be learned. To obtain real information about dielectrics, we must go beyond the Boltzmann-Hopkinson principle, out of the range where it applies.

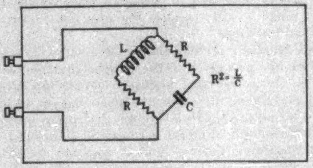

FIG. 2

Professor Murnaghan recognizes this situation and brings it out in the last part of the abstract which to my mind is the most important result of his paper. He says it goes somewhat further and shows that the principle is valid for any theory which leads to a system of linear differential equations with constant coefficients.

This overthrows any peculiarly preeminent place for the Maxwell Theory.

Let me now raise the question—over what range is the Boltzmann-Hopkinson principle valid? In almost any physical system, if small enough values of the variables are considered, as small velocities or small forces, we find that the system is described by means of linear differential equations. Hence the Boltzmann-Hopkinson principle or an equivalent principle should apply to almost any physical system if only the variables are kept small enough. Since this is true of almost every physical system, we say no more about a dielectric when we say that it satisfies the Boltzmann-Hopkinson principle for small values of electric forces, than if we say that it satisfies the law of conservation of energy.

Now, over what range does experiment show the superposition principle to be true? We do not need to go back very far in our own literature to get many cases where the Boltzmann-Hopkinson principle fails. In fact it seems that if any reasonable range of voltage gradient is considered, the principle is not valid. Curtis, in his very excellent paper of last summer on the "Conductivity of Dielectrics" says that below three to four hundred volts per cm. the conductivity currents in liquid dielectrics are proportional to the voltage, but for higher voltages, in some cases a saturation current is obtained and in other cases the current may increase more rapidly than in proportion to the voltage. Just recently a paper by Toryama has appeared in the *Archiv fur Elecktrotechnik* giving curves for the conductivity of transformer oil. These curves of current against voltage are convex downwards for all voltages from zero to breakdown. Of course if we limit ourselves to a small enough portion next to the origin, that portion may be regarded as straight, and that, I believe, is all there is to the Boltzmann-Hopkinson principle applied to dielectrics.

**V. Karapetoff:** This discussion sounds somewhat like an obituary of the Boltzmann-Hopkinson principle, and probably even the author will agree that the principle is inadequate, and yet like anything else in the progress of science it was necessary at one time until it has been worn threadbare. We see now that any hypothesis that leads to a system of linear differential equations with constant coefficients will give similar results, but essentially the shortcoming of this principle lies in the fact that it tries to build an ultra-microscopic structure and behavior of dielectrics on the basis of macroscopic images. In other words, this is one of those theories which may be called "bulk theories," that is, trying to account for the ultimate structure of matter by using images borrowed from the experience of our senses.

Seeing that we are now in a transition state to something more refined, and even ideational rather than material, I have felt a need for a word which would characterize the present outgoing theories, and so I have coined the adjective "macrocosmomorphic." "Macro" means "big;" "cosmos" means "the world;" and "morphic" means "of the shape of." Thus the word means built like the big world. The Boltzmann-Hopkinson principle is macrocosmo-morphic and therefore is destined to fall. We know from studies of X-Rays that simple crystalline bodies contain atomic lattices. For instance, rock salt contains alternate atoms of sodium and of chlorine in a definite arrangement, and so both the results of a mechanical stress or of an electrical stress applied to a crystal of rock salt must be expressed in terms of deformation of lattices and not of fictitious layers. Much of the advanced work done in Europe by Joffe, Rogowski, Smekal, and others, is directed toward a study of these lattices. Perhaps they are also macrocosmo-morphic, but at any rate a little more refined than plain layers. So we shall have to suck this new theory dry and then go to something still more refined.

**E. R. LeGhait:** In the discussion of the comparative advantages of micro and macro structures of dielectrics as bases for the explanation of the phenomena, I think it is well to bear in mind the wide range covered by the latter.

These phenomena are caused fundamentally by displacements of charges that lag behind the variations of the electromotive force. To explain this fact, some theories assume a certain viscosity within the atom that impedes the displacement of the electrons and causes an actual lag in polarization. Maxwell and his followers consider on the contrary that the lag of the displacements is not due to a lag in polarization but to the fact that it is the voltage distribution inside of the dielectric that lags behind the variations of the applied electromotive force. They thus look upon the dielectric as a conglomerate of particles that separately would possess only the properties of specific inductive capacity and conductivity and would not have any absorption. Of these two points of view, one based on a microstructure of the dielectric and the other on a macro structure, which is to be preferred?

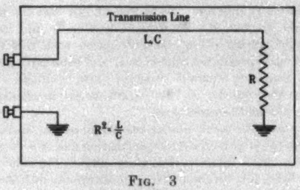

FIG. 3

I do not think it is either possible or desirable that all the anomalous phenomena of a given dielectric be explained on the basis of the same structure. I think that for the phenomena involving a considerably long duration of time, like losses at low frequencies, a macro structure ought to be considered, and that for those where very short durations of time are involved like losses at high frequencies, it is a micro structure that is the most suitable.

I believe that when one studies the anomalous properties of insulation and in particular the dielectric losses of impregnated paper at commercial frequencies, one finds great experimental evidence in favor of Maxwell's theory, or at least in favor of the idea at the basis of that theory, which is that the phenomena are due to the presence in the dielectric of materials of different specific inductive capacities and conductivities.

The observed variations of dielectric power factor of such insulation with frequency and temperature as well as absorption measurements point out in favor of the opinion that these effects are due to extra-molecular currents inside of the dielectric in accordance with the Maxwell theory.

Dr. Slepian expressed the opinion that the study of the anomalous effects was incapable of giving any indication on their ultimate cause and deplored the impossibility of opening up the dielectric and seeing what was inside of it. In connection with this it is interesting to make tests on paper while it is being dried out. Such tests show very clearly the influence of the presence of particles of a material of high conductivity (moisture in this case, imbedded in the dielectric) on its anomalous properties, and are a further confirmation of the value of the Maxwell theory.

However, I think that this theory as well as any assumed structure of the dielectric in accordance with it ought to be considered as merely explaining the anomalous properties within a certain range with a sufficient degree of approximation. In view of this, I think that one ought not to consider the heterogeneous dielectric as a conglomerate of particles of different materials that separately would only possess the properties of specific inductive capacity and conductivity with the exclusion of any kind of anomalous property. Let us remember that a perfect dielectric having only the property of specific inductive capacity can be looked upon as composed of atoms inside of which electric charges may be displaced, imbedded in a medium of infinitely high resistivity, the inter-atomic spaces. Such a dielectric can be considered as the limit case of a dielectric that would show only anomalous properties involving infinitely high and infinitely low time constants.

I think that instead of considering the composing materials of a heterogeneous dielectric as not having any kind of anomalous property one should merely consider them as not capable of showing alone any anomalous phenomena involving time constants of the same order of magnitude as those entering in the phenomena caused by their juxtaposition in the dielectric.

**F. D. Murnaghan:** There seems to be an impression in the minds of some readers that my paper is an advocate's brief pleading for a favorable view of Maxwell's Theory of Dielectric Absorption, but this impression is not correct. Professor Whitehead wished to give the theory a clear test and in order to do so found it necessary to complete in some points the mathematical argument and this was solely what I intended to do. Dr. Slepian's quotation from Professor Wilson's paper is, therefore, quite à propos; my paper is intentionally vacuous of physics and those who watch with interest the ever shifting sands of physical speculation may therefore justly charge me with trying to give my paper a permanent rather than a temporary value.

In the interest of frank discussion I must disagree with Professor Bush's comment that "Carson's proofs and modified forms furnish an excellent and complete guide to its (*i. e.*, the superposition principle) validity and use." When I first became interested in the present question I had access to Carson's interesting papers but found that my rather unintelligent use of his results led me into deep and troubled waters. What was the trouble? Carson was dealing with solutions of certain linear differential equations so that, in the first place, his work had to do *not* with the *current* but with the *displacement* in the various layers of the layer dielectric. In the second place a differential equation, by itself, is not a well set problem; one must know the initial conditions or values of the unknowns and their derivatives. The initial values of the displacements in our problem are not zero and I presume that Carson had in mind only the case when the initial values of the unknowns are zero. Be that as it may, his formulas do not apply to the present case which was the statement and proof of the superposition principle for the *current*. I feel it necessary to make these remarks as it would otherwise seem that I was thrashing very old straw indeed. The fact is that, in my opinion, even the men in high places quote incorrectly the superposition principle; to be explicit I have not seen my formula (**17**) in the literature although I have seen others which, if I read them aright, are incorrect.

# Symposium on Interconnection

## Conowingo Hydroelectric Project with Particular Reference to Interconnection

BY W. C. L. EGLIN[1]

Fellow, A. I. E. E.

*Synopsis.—This paper discusses the interconnection between three of the leading power supply companies in the eastern part of the country, the Philadelphia Electric Co., the Pennsylvania Power & Light Co., and the Public Service Electric & Gas Co. It outlines the physical aspects of the tie-in between the companies which is a 220-kv. ring of high-load capacity, triangular in shape with sides respectively 49 mi., 82 mi., and 77 mi. long. The advantages of the interconnection are enumerated as well as some of the operating problems.*

*Preliminary to the discussion of the interconnection the paper discusses the Conowingo hydroelectric project, an important factor in the interconnection scheme. The plant has an initial installation of 280,000 kv-a. in generators.*

* * * * *

AS a sound basis for developing the relation between the Conowingo project and the three-party interconnection agreement recently completed between The Philadelphia Electric Co., the Pennsylvania Power & Light Co., and the Public Service Electric & Gas Co., it seems advisable to begin by restating briefly the more important features of the Conowingo project. However, it is not the intention to duplicate in this paper the excellent work which has been done by many writers in presenting detailed information on all phases of the preliminary investigation, design, construction, and proposed operation of the Conowingo project.

### CONOWINGO PROJECT—GENERAL

The total drainage area of the Susquehanna River basin, as indicated in Fig. 1 is 27,400 sq. mi. divided as follows:

In Pennsylvania, 21,060 sq. mi. (77 per cent of the drainage area and 47 per cent of the area of the State)

In New York, 6080 sq. mi. (22 per cent of the drainage area and 13 per cent of the area of the State)

In Maryland, 260 sq. mi. (1 per cent of the drainage area and 2 per cent of the area of the State)

The boundaries of the drainage area in Pennsylvania are quite familiar to most persons, but the extension of the watershed in New York, northward almost to Utica, and eastward to about 40 mi. from the Hudson River near Albany, is probably less well known.

The Conowingo dam, on account of its location a few miles above tide water, intercepts the run-off from practically this entire area. United States Weather Bureau records over a long period of years indicate the precipitation to vary from 31.4 to 44.3 in. per year, averaging 39.4 in.

In making preliminary studies on the economic desirability of proceeding with the project, a long series of river-flow records was required. Since such records were available for Harrisburg, and the added drainage area between Harrisburg and Conowingo is almost exactly 12.5 per cent of that above Harrisburg, it has been assumed throughout that the flows at Conowingo are 12.5 per cent greater than at Harrisburg. According to the flow records from 1891 to 1926, the average annual discharge at Harrisburg varied from 21,600 sec. ft., (a run-off of 12.2 in. over the drainage area), to 52,600 sec. ft., (a run-off of 29.7 in.). The average for the period was 35,300 sec. ft., (a run-off of 19.9 in.), or about 50.5 per cent of the average precipitation.

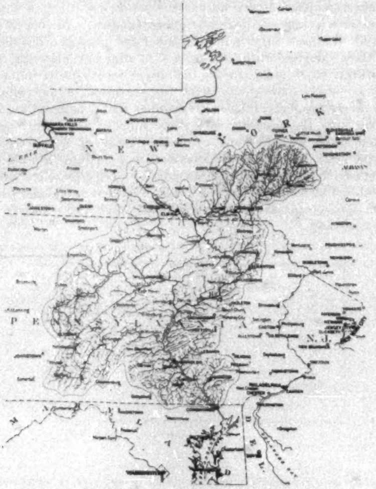

FIG. 1—SUSQUEHANNA RIVER DRAINAGE AREA

The extremely variable flow, both seasonally and from day to day, of the Susquehanna River is not sufficiently emphasized in the foregoing average values. Fig. 2, containing superimposed hydrographs plotted from Harrisburg data, with an auxiliary scale for

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[1] Vice-president and Chief Engineer, The Philadelphia Electric Company.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., February 13-17, 1928.*

**correction to Conowingo, brings out more clearly the variation of the monthly average between the winter and spring high flows, and the low flows of summer and fall, but even this figure cannot illustrate the extent of the low-flow periods in any particular year. About 6000 sec. ft. of water at full load is required for each of the seven units initially installed. The records indicate that several times the average flow of the river at Conowingo was less than 6000 sec. ft. for four months or more, while in one period of 4½ months (concluding with the first half of December, during which the annual peak of The Philadelphia Electric Co. System frequently occurs) the average flow did not exceed 5000 sec. ft.**

**It is this feature, more than any other, which has prevented the construction of a power plant in this reach of the river earlier, since the project has been studied for about forty years almost continuously by various competent organizations. High-capacity, initial installation was imperative on account of the size of the dam. This precluded independent operation and building up of local load and involved transmission to existing load centers together with the provision of expensive, relay, steam-generating capacity for use in the low-flow periods.**

**That the project has now become economically justified is because The Philadelphia Electric Co. sys-**

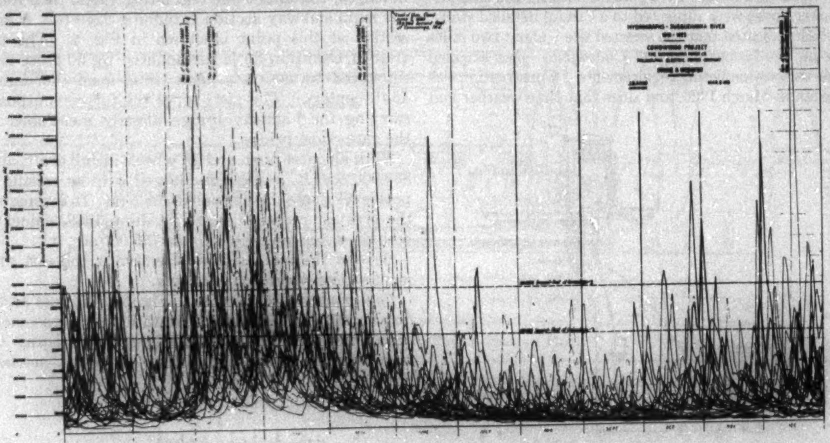


Fig. 2—Composite Hydrograph of the Susquehanna River

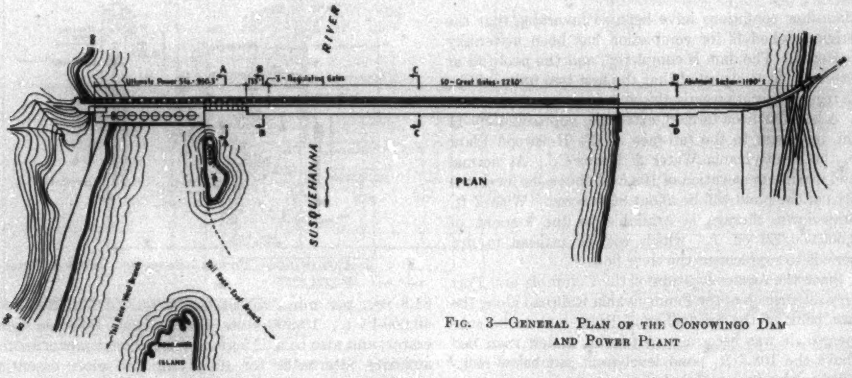

RIVER
Ultimate Power Sta. - 960.5'
A
B
135'
3 - Regulating Gates
C
50 - Crest Gates - 2250'
D
Abutment Section - 1190'±
SUSQUEHANNA
PLAN
Tail Race - West Branch
Tail Race - East Branch
ISLAND

Fig. 3—General Plan of the Conowingo Dam and Power Plant

tem load is large enough to absorb nearly the entire output of the plant at all times; while operation in connection with the existing steam stations in Philadelphia (utilizing Conowingo Station on the base of the load in high flows and on the peak in low), makes relay steam capacity unnecessary.

*Conowingo Dam.* Five possible sites for the dam and power house were subjected to a careful detailed study, which indicated that the selected site—about two miles below the former village of Conowingo—best satisfied the various conflicting requirements. Construction was begun in March 1926, and since that time weather and river-flow conditions have been so favorable that the original schedule for completion has been materially bettered. The dam is completed, and the pool full at present. It is expected that the first two units will be in regular operation early this year.

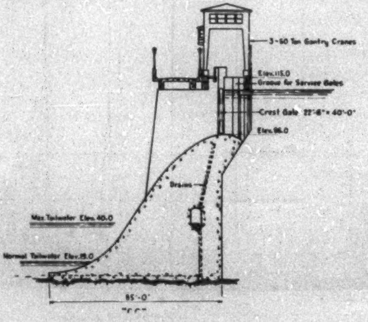


FIG. 4—CROSS-SECTION OF MAIN SPILLWAY SECTION CONOWINGO DAM

A lake has been formed, extending approximately 14 mi. upstream to the tail-race of the Holtwood Plant of the Pennsylvania Water & Power Co. At normal and maximum elevation of 108.5 ft. above sea level, the area of the pond will be about 8600 acres. With 7 ft. draw-down, storage is available to the amount of 2,500,000,000 cu. ft., which will be utilized in dry periods to supplement the river flow.

Since the former location of the Columbia and Port Deposit Branch of the Pennsylvania Railroad along the east bank of the Susquehanna River was to be submerged, it was necessary to provide a new road bed above the 108.5 ft. pond level from just below Holtwood to the dam and, below the dam, dropping down at a maximum of 0.35 per cent to the original grade at Port Deposit—about 16 mi. in all.

The Philadelphia-Baltimore Pike has been relocated so as to cross the river on a bridge placed on top of the dam structure. This bridge superseded the old steel bridge upon its demolition and flooding.

The dam is a gravity-section, concrete structure. As indicated in the plan, Fig. 3, starting from the west (left) side, an abutment section approximately 100 ft. long adjoins the power station section, 950.5 ft. long. The headworks structures for the four future units, as well as for the seven to be installed at this time, have been completed. The next section of the dam, 135 ft. in length, contains three regulating gates; then follows the main spillway section extending 2250 ft. A cross-section at this point is shown in Fig. 4. The fixed crest at elevation 86 is surmounted by 50 crest gates, supported by concrete piers rising from the dam on 45-ft. centers. The piers serve the further purpose of carrying the highway bridge already mentioned and the gate-crane bridge.

With all gates open and all wheels at full draft, about 880,000 sec. ft. will be discharged without raising the pool level above the normal of 108.5 ft. In comparison, the greatest recorded flood (in June 1889, coincident with the Johnstown Flood) was 750,000 sec. ft.

Beyond the main spillway section is the east abutment section about 1200 ft. long.

*Conowingo Power Station.* Fig. 5 is a cross section and Fig. 6 a plan of the power station. Seven generating units are initially installed, each consisting of a turbine of 54,000 hp. at full gate and 89 ft. net head, 81.8 rev. per min., direct connected to a 36,000-kw., 40,000-kv-a., 13,800-volt, three-phase, 60-cycle generator, and also to a 715 kv-a., 70 per cent power factor auxiliary alternator for supplying the more essential auxiliaries, namely the ventilating fans, governor pump, and unit exciter.

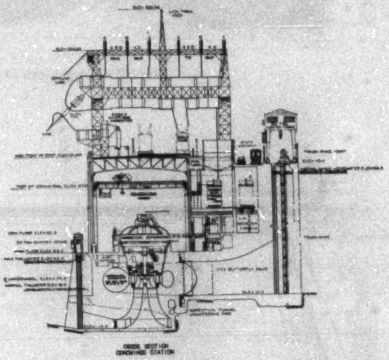


FIG. 5—CONOWINGO POWER STATION CROSS-SECTION

The generators, coupled in pairs, feed four 80,000-kv-a., 13.8/220-kv., transformer banks placed in open top compartments immediately above the 13.8-kv., switch structures. One extra 26,667-kv-a. transformer is provided as a spare for the four banks.

The output of the step-up transformers is controlled by the 220-kv. switching station on the roof of the power plant. The single line diagram, Fig. 7, indicates the four transformer banks and two 220-kv. lines now installed, and also the two banks and one line to be added upon completion of the ultimate installation of the power station.

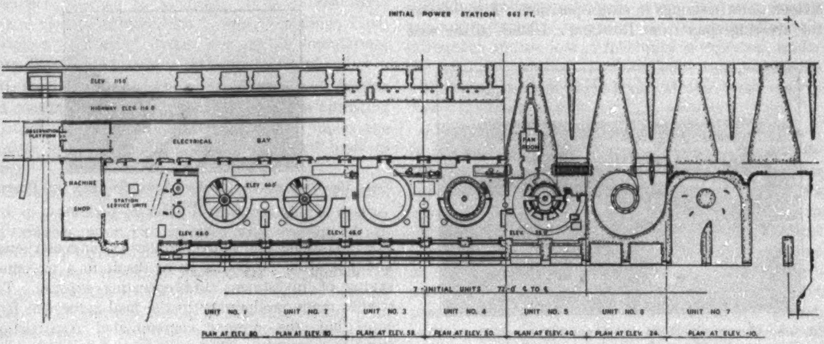

INITIAL POWER STATION 663 FT.
ELEV. 115.0'
HIGHWAY ELEV. 114.0
OBSERVATION PLATFORM
ELECTRICAL BAY
MACHINE SHOP
STATION SERVICE UNITS
ELEV. 60.0'
ELEV. 48.0
ELEV. 48.0'
ELEV. 38.0'
FAN ROOM
7-INITIAL UNITS 72'-0" ℄ TO ℄
UNIT NO. 1
UNIT NO. 2
UNIT NO. 3
UNIT NO. 4
UNIT NO. 5
UNIT NO. 6
UNIT NO. 7
PLAN AT ELEV. 80.
PLAN AT ELEV. 80.
PLAN AT ELEV. 58.
PLAN AT ELEV. 50.
PLAN AT ELEV. 40.
PLAN AT ELEV. 24.
PLAN AT ELEV. -10.

Fig. 6—Conowingo Power Station Plan

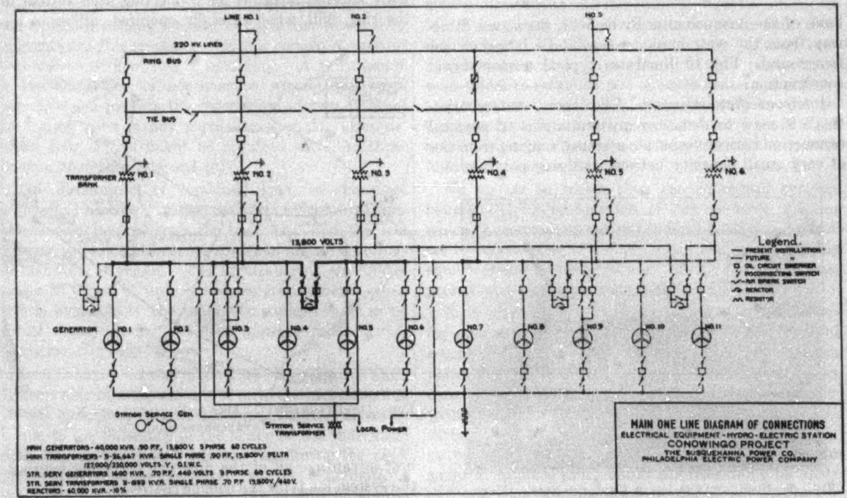

LINE NO. 1
NO. 2
NO. 3
220 KV LINES
RING BUS
TIE BUS
TRANSFORMER BANK
NO. 1
NO. 2
NO. 3
NO. 4
NO. 5
NO. 6
13,800 VOLTS
GENERATOR
NO. 1
NO. 2
NO. 3
NO. 4
NO. 5
NO. 6
NO. 7
NO. 8
NO. 9
NO. 10
NO. 11
STATION SERVICE GEN.
STATION SERVICE TRANSFORMER
LOCAL POWER
Legend.
— PRESENT INSTALLATION
— FUTURE "
☐ OIL CIRCUIT BREAKER
/ DISCONNECTING SWITCH
AIR BREAK SWITCH
REACTOR
RESISTOR
MAIN GENERATORS - 40,000 KVA. .90 P.F., 13,800 V. 3 PHASE 60 CYCLES
MAIN TRANSFORMERS - 3-26,667 KVA. SINGLE PHASE .90 P.F., 13,800 V. DELTA
127,000/220,000 VOLTS Y, O.I.W.C.
STA. SERV. GENERATORS 1600 KVA. .70 P.F., 440 VOLTS 3 PHASE 60 CYCLES
STA. SERV. TRANSFORMERS 3-833 KVA. SINGLE PHASE .70 P.F. 13,800V./440V.
REACTORS - 60,000 KVA. -10%
MAIN ONE LINE DIAGRAM OF CONNECTIONS
ELECTRICAL EQUIPMENT - HYDRO - ELECTRIC STATION
CONOWINGO PROJECT
THE SUSQUEHANNA POWER CO.
PHILADELPHIA ELECTRIC POWER COMPANY

Fig. 7—Single-Line Diagram of the Conowingo Power Station

Fig. 8 is a late view of the dam and power station from the west bank down stream.

### 220-Kv. Lines

The 220-kv. transmission lines from Conowingo Power Station to Plymouth Meeting Substation (approximately 65 mi. long) are carried on steel towers with a normal span length of approximately 1100 ft. The right-of-way width is 315 ft. which provides for three single-circuit tower lines spaced 85 ft. apart. The two outer tower lines have been built initially, resulting in a present spacing of 170 ft. between lines. The three conductors of each line are 795,000-cir. mils aluminum steel, reinforced, and are arranged horizontally with a spacing of 25½ ft. Each tower line also carries two 183,000-cir. mils aluminum steel, reinforced, ground wires. The conductors and ground wire on suspension type towers are carried on a new type of clamp which releases the conductor, and thereby relieves the tangent towers of excessive longitudinal stresses in the event of wire failure. The insulators are of a high-strength type with fourteen units in suspension strings and sixteen units in strings in strain position. Fig. 9 shows the crossing span from Rowland's Island to the east bank of the Susquehanna River, with the access cableway from the west bank to Rowland's Island in the foreground. Fig. 10 illustrates typical tangent-tower construction.

Fig. 8—Conowingo Dam and Power Station, from West Bank—Downstream Side

*Interconnection—General.* The term "interconnection" is used to denote many gradations of physical connection between separate systems, ranging from ties of very small capacity between outlying points of adjoining or interpenetrating systems (which, if utilized to the utmost, could not materially affect the operating economies of the system taken as a whole), up to trunk lines connecting principal centers of load and generation, involving a comprehensive mutual program with large investment, and promising commensurate return. To the latter class belongs the interconnection between The Philadelphia Electric Co., the Pennsylvania Power & Light Co. and the Public Service Electric & Gas Co., the first step of which is now practically ready for operation. It is the purpose of the three companies by this interconnection so to coordinate their construction and operation programs as to result in a maximum saving of investment and operating expense. The studies made preliminary to the final agreement indicate that the present contemplated construction, namely, a complete 220-kv. ring between the systems with suitable facilities for connecting each system to the ring, will, when carefully operated, utilize to the best advantage all of the diversity occurring between the system loads for the coming ten years.

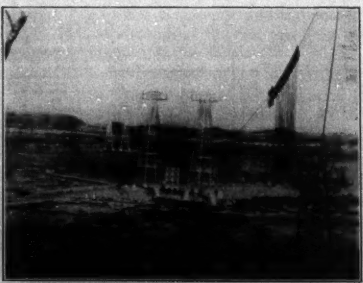
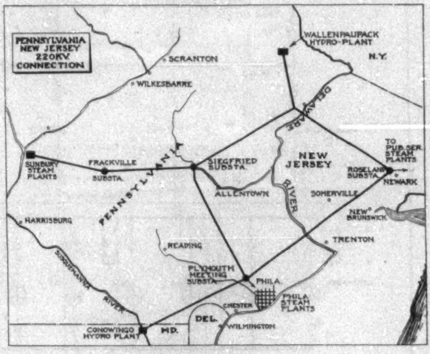


Fig. 9—Susquehanna River Crossing Span. Rowland's Island to East Bank. Access Cableway from West Bank to Rowland's Island in Foreground

Fig. 10—Conowingo 220-Kv. Line Towers at Porters Bridge



PENNSYLVANIA NEW JERSEY 220KV. CONNECTION
SCRANTON
WILKESBARRE
WALLENPAUPACK HYDRO-PLANT
N.Y.
DELAWARE
SUNBURY STEAM PLANTS
FRACKVILLE SUBSTA.
PENNSYLVANIA
SIEGFRIED SUBSTA.
ALLENTOWN
NEW JERSEY
RIVER
TO PUB. SER. STEAM PLANTS
ROSELAND SUBSTA.
NEWARK
SOMERVILLE
NEW BRUNSWICK
HARRISBURG
TRENTON
READING
PLYMOUTH MEETING SUBSTA.
PHILA.
SUSQUEHANNA RIVER
PHILA. STEAM PLANTS
CHESTER
DEL.
WILMINGTON
CONOWINGO HYDRO PLANT
MD.

Fig. 11—Diagrammatic Map of Pennsylvania-New Jersey Interconnection

The points selected as terminals of the 220-kv. ring, forming roughly, an equilateral triangle, are: Plymouth Meeting near Norristown, for The Philadelphia Electric Co.; Siegfried near Allentown, for the Pennsylvania Power & Light Co.; and Roseland near Newark, for the Public Service Electric & Gas Co. The actual distances (line mileage) are: Plymouth Meeting to Siegfried, 49 mi.; Siegfried to Roseland, 82 mi.; Roseland to Plymouth Meeting, 77 mi.

Fig. 11 shows a diagrammatic map of this interconnection. A portion of the existing line from Wallenpaupack Hydroelectric Station of the Pennsylvania Power & Light Co. will be utilized as a portion of the Siegfried-Roseland line when this is built.

The line now practically completed, is that from Plymouth Meeting to Siegfried. It is of the same general type of construction as the Conowingo Line, though a number of details relating to foundation, tower design, and insulators were not identical.

In the interconnection plan, each company designs and constructs the lines lying within its own operating territory, although all three have agreed upon the climatic loading conditions and the general basis of design.

There are many points at which saving can be made, both in generating-capacity investment and in operating expenses, when two or more large systems of approximately equal system loads are interconnected by tie lines heavy enough to interchange any amount of energy which the economics of the situation may require. The principal saving in this case results from load diversity, in that the peak load of the combined systems is smaller than the sum of the individual peaks. A second important factor is reserve diversity, since the companies by pooling the reserve capacities which they maintain are able to dispense with a certain portion of this reserve without loss of reliability. A third factor is the staggering of construction among the companies, which permits the installation of two or three generating units in any particular year, for example, where four or five might be required with the three systems operating independently.

The distribution of combined load, in the most economical manner utilizing the more efficient stations of the combined systems for base load and the less efficient as peak stations, is a source of material savings in operating expenses. The furnishing of emergency power in excess of normal reserve requirements when this is available in the other companies results in no actual money saving but does improve reliability of operation.

*Load Diversity.* Load diversity between two or more systems may be analyzed into several distinct elements. In this case the principal portion of the load diversity is due to the difference in the shape of the individual daily load curves on any selected day during the peak period of the combined systems. Further contributions are made by the difference in the season of annual peak and by the non-coincidence of those accidental high days which cause weekly or monthly peaks on the individual system. As an instance, throughout the year the daily peak load of the Pennsylvania Power & Light Co. is in the morning, with the afternoon load slightly lower and the evening load materially reduced. Their annual peak load occurs in October.

The load curves of the Public Service Electric & Gas Co. and The Philadelphia Electric Co. are quite similar, both containing large evening loads throughout the year, and in particular a high peak near 5:00 p. m. throughout the winter months. The yearly maximum load of both usually is found in December.

*Reserve Diversity.* The experience of the three individual systems with calls upon their own reserve generating capacity indicates that these are relatively infrequent and no loss in reliability is expected, under the assumption that the interconnecting companies will not all require their share of the total reserve diversity simultaneously.

*Economic Distribution of Combined System Load.* In a single system of steam generating stations, especially when serving a compact territory, the proper apportionment of load among stations seldom offers serious difficulties. It is usually found economical, as the system grows, to build up one station at a time from initial to ultimate capacity rather than to have two or more under way, simultaneously. Thus each station in its operating performance reflects current practise during its design and construction period, and the cost margin between stations is sufficient to render obvious the correct distribution of load. Transmission limitations and minimum loading requirements of stations may enforce departures from this ideal distribution. In the case of a system of wide area and low concentration of load, it may prove more economical to establish two or more centers of supply, and increase them in capacity according to the requirements of their districts, rather than to provide the transmission facilities required to permit all the growth to take place at one station.

No matter to which class the concerned systems belong, the interconnection of two or more systems which have grown up entirely independently, and which are therefore likely to include stations of approximately equal-operating performance, offers many delicate problems of load apportionment.

*Load Dispatching.* The interconnection headquarters for general administration and load dispatching is to be established at Siegfried. The load dispatchers at this point will be in direct communication at all times, through the load dispatchers of the individual systems, with the steam and hydrogenerating stations of the three companies. They will be advised of the expected outputs from the various hydro plants of the system as far in advance as estimates can reasonably be made, and will plan the operation of the steam stations to carry most economically the remaining load. Load records, metering, etc., will all center here. The preliminary studies of the interconnection project have demonstrated conclusively that an opportunity for large savings exists, but only the most alert and skilled load dispatching will realize all of the possible benefits.

The detailed technique of interconnection operation has not been entirely worked out as yet, but the two companies which are immediately to be connected by the Plymouth Meeting-Siegfried line are in close touch with one another on these matters, and before operation commences will have worked out a complete schedule.

*Stability and Reliability.* While a detailed discussion of the stability and reliability of the 220-kv. interconnection lines is out of place in the present paper, it can be stated that these considerations were among the foremost governing the entire study and design. It is expected that adequate stability under all loading conditions will be afforded the 220-kv. ring by the synchronous condensers located at the terminal substations (in the case of The Philadelphia Electric Co., initially 90,000 kv-a.).

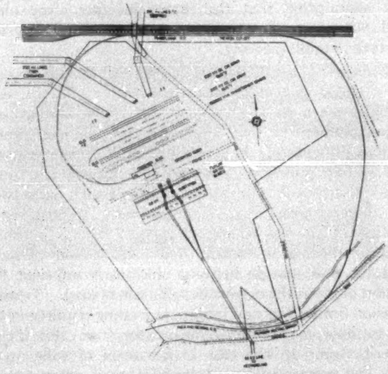
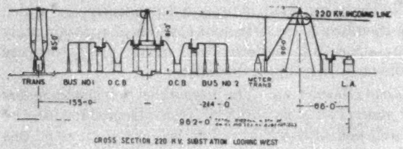
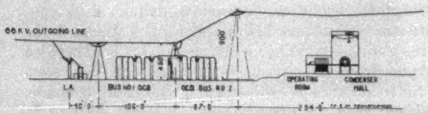


FIG. 12—PLOT PLAN OF THE PLYMOUTH MEETING SUBSTATION



CROSS SECTION 220 K.V. SUBSTATION LOOKING WEST



CROSS SECTION 66 K.V. SUBSTATION LOOKING WEST

FIG. 13—PLYMOUTH MEETING SUBSTATION CROSS-SECTION

## CONNECTIONS FROM 220-KV. LINES TO THE PHILADELPHIA CO. SYSTEM

*Plymouth Meeting Substation.* Plymouth Meeting Substation, the junction point for the 220-kv. Conowingo and Interconnection lines, and the 66-kv. lines to Philadelphia, was laid out on a tract of about 40 acres, as shown by Fig. 12. The Conowingo and Interconnection lines terminate at the 220-kv. buses, to which are also connected the 220/69-kv. transformers tying in with the 66-kv. lines to Westermoreland Substation in Philadelphia.

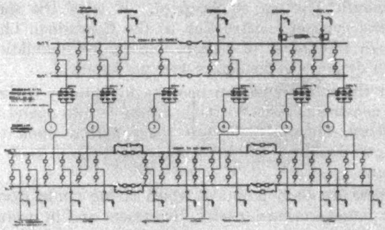


FIG. 14—SINGLE-LINE DIAGRAM OF PLYMOUTH MEETING SUBSTATION

As the cross-section (Fig. 13) and the single-line diagram (Fig. 14) indicate, two 220-kv. buses are installed, provision being made for an ultimate of five 220-kv. lines and six transformer banks, with each bus sectionalized by an oil-circuit breaker. Any bank or line may be connected to either 220-kv. bus, through breakers. The initial installation consists of three lines, two from Conowingo and one from the Siegfried Substation of the Pennsylvania Power and Light Co., and two transformer banks, together with a portion of both buses.

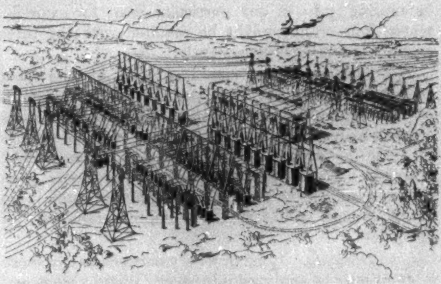


FIG. 15—PERSPECTIVE SKETCH: PLYMOUTH MEETING SUBSTATION

A more comprehensive view of the substation, although not accurate in all details, is given by the perspective sketch, Fig. 15. On the 66-kv. side of the substation, two buses will be installed with provision for an ultimate of twelve 66-kv. lines, together with the six transformer banks. Sectionalizing is provided for at two points in each bus. The initial installation consists of two lines to Philadelphia, and two to the Philadelphia Suburban Counties Gas and Electric Co., and parts of both buses.

A condenser building and a control room are located between the 220-kv. and 66-kv. sections of the station.

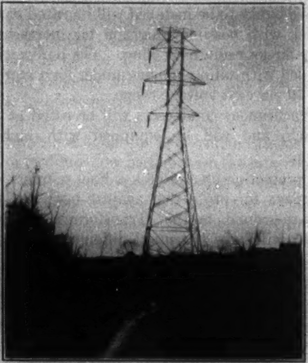


Fig. 16—Two-Circuit Tower—Plymouth Meeting—Westmoreland 66-Kv. Line

Three condensers are being installed initially, with provision for an ultimate of six units.

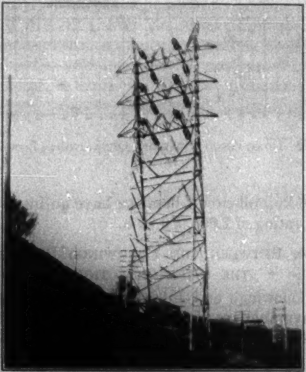


Fig. 17—Four-Circuit Tower—Plymouth Meeting Westmoreland 66-Kv. Line

The transformer banks are self-cooled with a nominal rating of 100,000 kv-a.; however, with the air-jet radiator cooling to be installed, their capacity will be increased to approximately 130,000 kv-a. These transformers are of the three-winding type, with the 220-kv. and 66-kv. windings connected star and solidly grounded. The delta, tertiary winding is rated at 13,300 volts. Ratio changing under load equipment, giving a voltage range of 15 per cent, is provided with these transformers.

The synchronous condensers, which are connected to the transformer tertiary windings, are each rated at 30,000 kv-a. and are equipped with extra high-speed excitation.

Relay protection on the 220-kv. lines consists essentially of special type *C Z* relays and directional, ground-current relays. Transformer banks and condensers have the usual differential protection. The 66-kv. lines are also protected by *C Z* and ground-current relays.

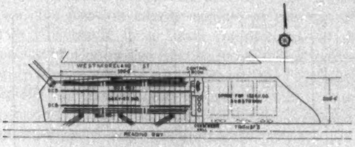


Fig. 18—Westmoreland Substation Plan

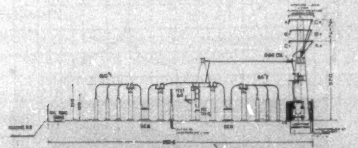


Fig. 19—Cross-Section of Westmoreland Substation

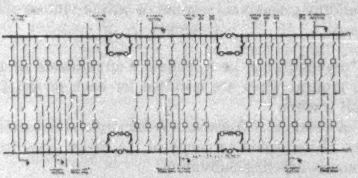


Fig. 20—Single-Line Diagram of Westmoreland Substation

The 220-kv. oil-circuit breakers have an interrupting capacity rating of 2,500,000 kv-a., and the 66-kv. line breakers a rating of 2,000,000 kv-a.

*66-kv. Lines.* The transmission lines, for connection from the 220-kv. system to the existing 66-kv. Philadelphia Electric Co. transmission system, are carried from the Plymouth Meeting Substation approximately ten miles to Westmoreland Substation in northern Philadelphia, generally following along the banks of the Schuylkill River. For approximately one-half of this distance the conventional two-circuit tower construction is used, with an average span length of 800 ft. (Fig. 16). On account of the limited space available for the remainder of the distance, a special type of four-circuit towers has been utilized; and some of these bridge the railroad right-of-way of the Reading Co. On this portion of the line, a normal tower spacing of 600 ft. has been adopted; and the towers located with a view to the requirements of future electrification catenary structure (Fig. 17). Two circuits each, of 500,000 cir. mils copper, have been constructed initially and provision has been made for an ultimate of six. Two ground wires are installed for each of the two circuit towers.

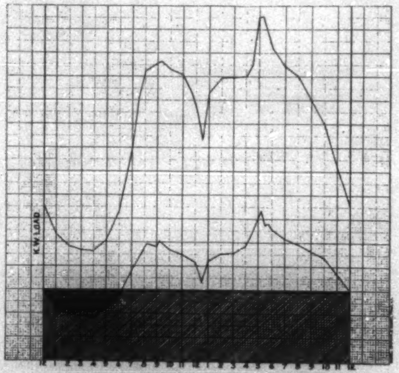


FIG. 21—CONOWINGO STATION OPERATION; HIGH-FLOW CONDITIONS

*Westmoreland Substation.* Westmoreland Substation is the Philadelphia terminus of the 66-kv. lines from Plymouth Meeting Substation.

As may be seen from Figs. 18, 19, and 20, the general scheme of connections and the physical arrangement of equipment are similar to those of the 66-kv. portion of Plymouth Meeting Substation and other Philadelphia electric 66-kv. substations, two 66-kv. buses being provided to which any line or transformer bank may be connected through oil-circuit breakers. At Westmoreland Substation, provision is made for an ultimate of twenty-three 66-kv. sections, five or six of which will be utilized by 66/13.2-kv. transformer banks, and the remainder by transmission lines to Plymouth Meeting Substation and to other 66-kv. substations of the Philadelphia Electric System. Bus sectionalizing, including reactors, if their use is found necessary, is provided for at two points in each bus.

The initial installation is two overhead lines to Plymouth Meeting Substation, two underground lines to Richmond Substation, two underground lines to Schuylkill Substation (together with portions of both buses), and two 66-kv. feeders to two 18,750-kv-a., 66/13.2-kv. transformer banks in a nearby substation. By late summer, two 66/13.2-kv. transformer banks and two synchronous condensers will be installed in the 13.2-kv. section of the station. Ultimately, three and possibly four transformer banks and three condensers will be installed.

The two banks to be installed will be rated at 60,000 kv-a. each with possible provision for increasing this rating by air-jet radiator cooling. The banks will also be provided with ratio changing under load equipment giving a 10 per cent voltage range.

The synchronous condensers will be rated at 30,000 kv-a. each, and will be equipped with high-speed excitation.

Relay protection on the 66-kv. lines consists of *C Z* duplex relays for protection against both line-to-line and line-to-ground faults. Transformer banks and condensers will have the usual differential protection.

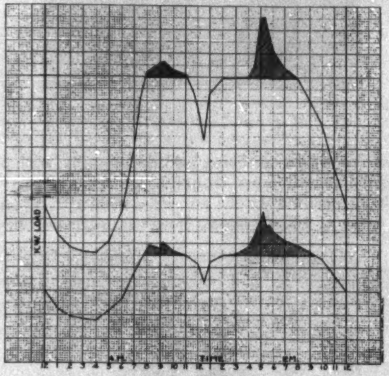


FIG. 22—CONOWINGO STATION OPERATION; LOW-FLOW CONDITIONS

The 66-kv., oil-circuit breakers have an interrupting capacity rating of 2,000,000 kv-a.

### RELATION BETWEEN THE CONOWINGO PROJECT AND THE INTERCONNECTION

The Conowingo and Interconnection projects have many favorable reactions upon each other. One of these is the common use of facilities for connecting the 220-kv. lines with the Philadelphia Electric Co.'s existing transmission system. The cost of Plymouth Meeting Substation and of Westmoreland Substation, for either the Conowingo project or the interconnection separately, would have been considerably greater than the proportionate share of the actual combined construction cost.

While two 66-kv. lines from Plymouth Meeting Substation to Westmoreland Substation would have been required for the Conowingo project alone, and one for the initial interconnection step alone, on account of the short period of simultaneous maximum demand, only two lines are being installed for both the first year.

The output of the Conowingo project can be completely absorbed earlier with the interconnection, since the minimum combined load of the three systems is well above the full load capacity of Conowingo Station. Likewise, Conowingo's value in replacement of steam generating capacity at all times of the year is greater with the interconnection.

Figs. 21 and 22 illustrate the more effective utilization of the water available for Conowingo Station, both in high-flow and low-flow periods with the interconnection. In Fig. 21, which represents winter, high-flow conditions, the lower load curve is that of the Philadelphia Electric Co. system alone, and the upper, that of the interconnected companies combined. The cross-hatched area indicates the energy that can be developed from the Conowingo Station, sufficient water being available to run all the turbines in the station at full-load for 24 hr. Operating in conjunction with the Philadelphia Electric Co. system load alone, the area indicated by the double-cross-hatching would be lost on account of the decrease of the system load below the capacity of the station during the night hours. On the other hand, operating with the interconnected systems, the minimum load is well above the capacity of Conowingo Station at all times, and the entire available energy can be utilized.

Fig. 22 illustrates winter, low-flow conditions, in which a very small amount of water per day may be available. In this case the economical method of operation is to utilize all of the available water energy in carrying the peak load, leaving the base load to the team-generating stations, since in this manner the hydro plant replaces the greatest amount of steam-generating capacity. The cross-hatched areas on the two curves are equal, and it will be readily noted that, utilizing exactly the same limited amount of water in either case, the replacement of other generating capacity by Conowingo Station is about 50 per cent greater when operated on the Interconnection load curve, than on that of the Philadelphia Electric system alone.

During the summer months, when the load curves of both the Philadelphia Electric Co. system alone, and of the interconnected systems, are nearly flat for several hours, the low-flow energy applied at the top of the curve will result in a lower replacement of steam capacity by Conowingo Station, possibly no greater on the Interconnection load than on the Philadelphia Electric Co. system load alone. At such times, on account of the short starting period required by hydro generating units, every generating unit not required for the normal load can be utilized as standing, reserve capacity for the entire interconnected system. The amount of expensive, steam-reserve capacity will thus be reduced.

It is hoped that this brief presentation of the largest interconnection yet attempted, embracing three of the leading power supply companies of the United States, and including Conowingo Station (in its ultimate capacity the largest single hydroelectric station), may be of value to all those interested in the general subject, and especially to those who find themselves faced by similar problems.

The author desires to express his thanks to Messrs. F. C. Ralston, R. A. Hentz, and P. H. Chase of the Philadelphia Electric Co., for their helpful assistance in collecting and compiling the material contained in this paper.

## Discussion

For discussion of this paper see page 408.

# Progress and Problems

## From Interconnection in Southeastern States

BY W. E. MITCHELL[1]

Fellow, A. I. E. E.

***Synopsis.****—Great progress has been made. Interconnection between independent systems is primarily a protective measure. The greatest economic benefits have been realized when the interconnections have been made by subsidiary companies of one holding company. The capacity of tie lines and the amount of power interchanged has increased greatly. The size of generating units has increased, as has the size of power plants, resulting in lowered cost per kw. The problem of satisfactory voltage and power factor control has increased in complexity as has that of system load dispatching. While much improvement has been made in oil circuit breakers, they still leave much to be desired. Interconnection has made possible more economical operation of existing plants and has resulted in the use of a larger proportion of the available water on systems combining steam, storage, and run-of-river hydroelectric plants.*

*Long-time forecasting of load and rainfall conditions is important in economical system planning. The 110-kv. and 154-kv. line construction is discussed, also the value of ground wires and lightning arresters. The growing importance of carrier current for supervisory control and communication and their application are discussed.*

* * * * *

IN 1924 in a paper on Interconnection of Power Systems in the Southeastern States, the author suggested that our great problem for the next 10 years would be to increase the capacity of the interconnecting links between different systems, to develop water power distant from the power market, and to construct the mine mouth or other strategically located (from an economic standpoint) high capacity steam plants, and connect them with the great load centers by means of high-capacity networks. He also suggested that we should plan for at least 10 years in the future.

Less than four years have passed, yet tremendous strides have been taken along these very lines. The economic possibilities of interconnection are being clearly realized. One of the results has been the coordination in a number of instances of the various individual operating companies under one holding company, thus deriving the benefit of massed capital, massed resources, and unified control. Interconnection, group management, low-cost steam generation, and long distance transmission have come as a logical succession of natural economic steps.

Interconnection between independent systems is, first, a measure of protection in emergencies. It cannot be a success unless the executives and operating forces of the respective companies realize it is a give-and-take proposition, and have mutual regard for the interests of both companies in the service of the public.

In the Southeast, what we term an "operating committee," (on which are representatives from Alabama Power Co., Tennessee Electric Power Co., Georgia Power Co., Columbus Electric and Power Co., Augusta-Aiken Railway & Electric Co., Southern Power Co., and Carolina Power and Light Co.) has been functioning for over four years. This committee meets about eight times a year and compares operating data, load, rainfall, storage reservoir conditions, and other problems of mutual interest. This has proved of the greatest value to all concerned. Getting better acquainted and the resultant better understanding, together with a greater knowledge of each others' systems and their points of strength or weakness, have facilitated the prompt handling of the exchange of power in emergencies. Frequently, improved operating economies through interchange have resulted from a greater knowledge of conditions throughout the entire territory.

Unquestionably the greatest benefits are derived, however, (and this applies both to the general public as well as to the individual companies), when the interconnected companies while maintaining their independent corporate identity are subsidiaries of one holding company. It is practically impossible to have a unified development program for five independent companies, but if these are under the same financial, engineering, and management control, then genuine system planning on a large scale will take place and the most economical plants and tie lines will be built first looking only to the maximum results for the group as a whole.

Electrical development in the Southeast has kept pace with the rest of the country as the tabulation on the following page will show.

The accompanying map, Fig. 1, shows the transmission lines of these companies covering a large part of seven of the most progressive states of the new industrial south.

The system of the Southeastern Power and Light Company is operated in parallel practically all of the time, and much of the time it is in parallel with both the Tennessee and Carolina systems. For successful parallel operation and, at the same time, to secure the proper load division between the various generating stations and between the systems themselves, it is essential that the frequency be very closely controlled.

We endeavor to maintain the frequency rigidly at 60 cycles. By the installation of master clocks at the

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[1] Vice-President and General Manager, Georgia Power Co., Atlanta, Ga.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., February 13-17, 1928.*

TABLE I

| | | 1923 | 1926 | 1927 |
|---|---|---|---|---|
| Installed generating capacity | Hydro-kv-a | 782,000 | 1,170,505 | 1,362,167 |
| | steam-kv-a | 353,000 | 497,978 | 622,487 |
| Total generation—kw-hr | | 3,250,000,000 | 3,822,718,019 | 4,150,000,000* |
| Peak load —kw-hr | | 740,000 | 800,000 | 870,000* |
| Hydro storage —kw-hr | | 225,000,000 | 265,700,000 | 418,000,000 |
| Miles of 110,000-volt lines | | .... | .... | 4,497 |
| Miles of interconnecting lines | | .... | .... | 538.41 |
| Interchange power between companies—kw-hr | | 228,500,000 | 457,000,000 | 573,000,000* |

*Estimated.

larger generating stations, and the use of extremely accurate frequency recorders at load dispatching centers, it has been possible to make material improvement in the control of frequency over the interconnected systems. Fig. 2 is a typical frequency chart taken when the Southeastern Power and Light Company system was operating in parallel with Tennessee Power Company. While this chart probably does not indicate as steady a frequency as exists upon metropolitan systems, it does show the narrow limits within which it is possible to regulate the frequency upon a very extensive system. It should be noted that one cycle is represented by a space of 2⅜ in. on the chart, so that a variation of 0.05 cycles covers about one-eighth inch.

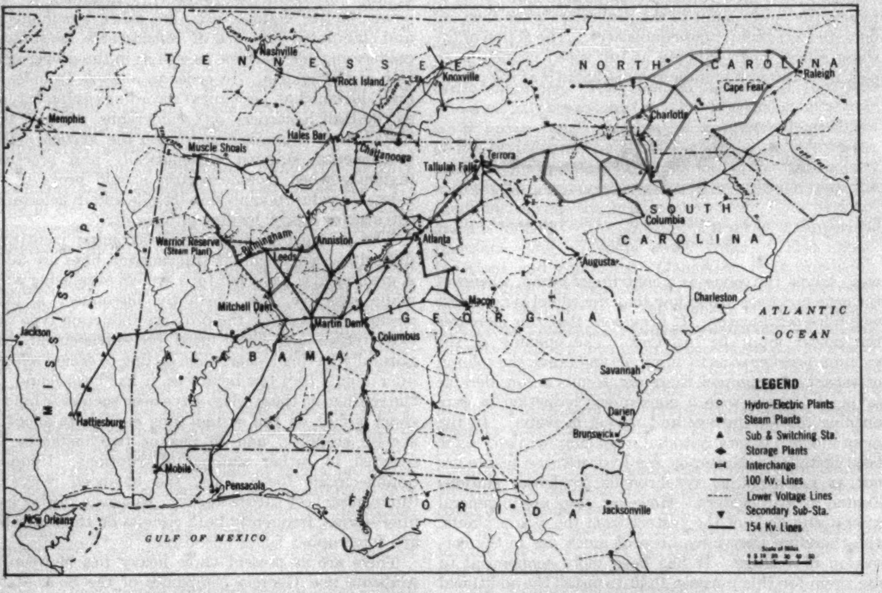
TENNESSEE
Nashville
Rock Island
Knoxville
NORTH CAROLINA
Raleigh
Cape Fear
Memphis
Charlotte
Hales Bar
Muscle Shoals
Chattanooga
Tallulah Falls
Terrora
MISSISSIPPI
SOUTH CAROLINA
Columbia
Warrior Reserve (Steam Plant)
Birmingham
Anniston
Atlanta
Leeds
Augusta
Macon
Charleston
Mitchell Dam
Martin Dam
GEORGIA
ATLANTIC OCEAN
Jackson
Columbus
ALABAMA
Savannah
Hattiesburg
Darien
Brunswick
Mobile
Pensacola
FLORIDA
Jacksonville
New Orleans
GULF OF MEXICO
LEGEND
Hydro-Electric Plants
Steam Plants
Sub & Switching Sta.
Storage Plants
Interchange
100 Kv. Lines
Lower Voltage Lines
Secondary Sub-Sta.
154 Kv. Lines
Scale of Miles

Fig. 1—Map Showing Transmission Systems in Southeastern States

During the wet season the basic load is carried by the run of river hydroelectric plants, and the load fluctuations by steam plants and vice versa during dry seasons. The system supplying the bulk of the power regulates the frequency. Special attention has been given to the adjustment of governors at all generating stations, so that they will be as nearly as possible equally sensitive, in order that all stations may carry their proper share of the load fluctuations.

The problem of voltage control grows more important and more complicated as larger systems are tied together and as additional interconnections are made. On the system of the Southeastern Power and Light Company, there is at present installed a total synchronous condenser capacity of 130,000 kv-a. This capacity is fairly well distributed over the system at important load centers. The condensers are all controlled by automatic voltage regulators. Three 5000-kv-a. condensers and one 10,000-kv-a. condenser are equipped for full automatic control; that is, from the starting to the stopping operation. Alabama Power Company has installed a 25,000-kv-a. turbo generator at the Gorgas steam plant, with provision for disconnecting the generator and the turbine and operating the generator as a synchronous condenser. During the wet season, when the steam unit is not required for supplying power, the generator is disconnected and operated as a synchronous condenser, supplying approximately 15,000-kv-a. corrective capacity to the system. In addition to this, the hydroelectric units are used for power factor correction, as required during the peak load hours, and when not required for supplying power. Usually, during the dry season of the year, when steam plants are operating on base load, a large portion of the hydroelectric capacity is used during peak-load hours for power factor correction. It is the practise, when these units are operating as synchronous condensers, to close the gates tightly. Vacuum breakers have been installed upon all of the more important units so as to reduce the power input to the generators when they are operated as synchronous condensers. The action of the water wheel when running at full speed is such as to pick up water at its center and discharge it at the perimeter, much the same as a centrifugal pump, whenever the gate openings are so low that the wheel is not fairly well filled with water. It is evident that this increases the power input to the unit. The opening of the vacuum breaker so as to admit air and break the column of water being pumped, therefore, results in considerable saving in losses, with a consequent reduction in gate opening for low ratings and saving in water. In the more modern plants, automatic vacuum breakers have been installed. Naturally the hydroelectric plants are not as beneficial as synchronous condenser stations located at load centers. However, they are in general at opposite ends of the system from the steam plants, and therefore they have been of much use in the correction of voltage. It has been more economical to use them for this purpose than to install the additional synchronous condenser capacity which would be required.

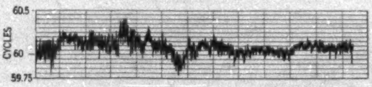

Fig. 2—Typical Frequency Chart of Southeastern Power & Light Co. System

It has not yet been found necessary to install regulating transformers in tie lines to govern the division of load and wattless current, but it is very likely that this or some other method will be required as the number of ties between the systems increases. With the increasing amount of load carried over the lines, the problem of system stability has been encountered. In 1926, when it was necessary to supply abnormal loads over two tie lines between Alabama and Georgia, frequently an outage of one of the tie lines due to lightning or other trouble would result in a separation of the Alabama and Georgia systems by pulling out the other tie lines. Operating experience indicates that with a load of 30,000 kw. on each line, an interruption on one line will result in the separation of the two systems. As a result of this experience, an extensive series of stability tests was made in cooperation with one of the larger manufacturers. A technical paper is now being prepared describing in detail these tests.

On a large network system, it is becoming increasingly difficult, and, in fact, practically impossible, to make the necessary calculations for load division over transmission lines, voltage regulation, etc. Therefore, the practise has been established of at least once or twice each year taking simultaneous readings at all of the most important generating stations and load centers of the interconnected network. Readings of load, power factor, voltage, etc., are taken simultaneously and tabulated and are of considerable assistance in engineering calculations, as well as in the proper operation of the system. In order to analyze troubles and provide remedies, permanent recording equipment, such as the Hall Recorders, or oscillographs, are now being installed at stragetic points upon the system. These instruments, starting automatically and practically instantly when trouble occurs, should prove of considerable value in analyzing trouble and in determining settings for relays, loading of lines, etc.

The problem of relaying is becoming increasingly difficult as single circuit transmission lines are added. A great need is being felt for a system of relaying which, while selective, will instantly disconnect a faulty circuit. At present, the ordinary induction type overload relays are being used on single-circuit lines, naturally having a short time setting to secure selective operation. In a few instances, it has been found that the settings on these relays have been such as to hold the short circuit on the system long enough to affect the system stability, and in one or two instances, has resulted in rather serious interruptions. Upon the double-circuit tower lines, the balanced relays are functioning very satisfactorily. However, during lightning storms, frequently both circuits on the tower lines are interrupted simultaneously.

There are at present three heavy ties between the Alabama and Georgia companies of the Southeastern Power and Light Company system—two direct and one through the Columbus Electric and Power Company. So far, the main flow of power has been from West to East and this will probably continue to be the case for about three more years. However, there are now numerous short periods when surplus run of river power is sent from Georgia to Alabama. So far we have been able with the existing synchronous condenser capacity to handle as much as 90,000 kw. over these tie lines and maintain satisfactory voltage conditions. Within four months a new 154-kv. tie., 145 mi. long, will be completed between Martin Dam and the East Point Substation at Atlanta of the Georgia Power Company. This tie will have a capacity of approximately 60,000 kw. It will be a single-circuit line of special cross-braced H frame steel towers, 60 ft. high with 39-ft. steel crossarms mounted 56 ft. above the ground. Conductor spacing is 19 ft. 6 in. Conductors will be 397,500 cir. mils A. C. S. R. with two No. 2/0 composite aluminum steel ground wires flexibly attached to the towers. Insulation for 154 kv. will consist of 11 units in suspension and 12 units double yoke on strain with grading shields used throughout the line.

On September 18, 1927 a 90-mi. line between Gorgas Steam Plant and Wilson Dam was put in operation at 154,000 volts, this being the highest voltage at present in use in the southeastern states. This line was built during the war and used at 110,000 volts until this changeover. The need of additional capacity caused the change-over. This line now has a capacity of 60,000 kw.

A third 154,000-volt line of the same type as the Martin-East Point line is practically complete now between Martin Dam and Leeds substation. For the present and until the construction of Lower Tallassee, this line will be operated at 110,000 volts.

The construction of these lines brings out forcibly the economy of unified control. They permit the postponing of the construction of additional power plants by one company until those under way by other companies under the same control are loaded up.

As the systems grow larger, interconnection between those under one management makes for greater operating efficiency. Full advantage is taken of diversity of time, diversity in rainfall, and in seasonal load. Without the tie lines this would be impossible. To a somewhat lesser degree, these same factors may be taken advantage of by means of ties between independent companies. With the large storage reservoirs practically no water goes to waste during the summer season. If one section has a heavy rain and another none, the tie lines permit sale of the surplus at such a price that the company that has had no rain can afford to buy power and store its own water. Matters of this nature are handled by the load dispatchers or operating engineers and may cover a period of a day, week, or even longer.

With the more careful studies of the curves of rainfall and run-off and expected load, a greater use is made of all hydroelectric plants. The run of river plants which on the isolated system wasted water all night long because it had little or no storage, now that it is linked into a comprehensive system, generates many more kw-hr. than it previously did, thereby probably saving fuel generation.

On a system combining run-of-river and storage hydroelectric plants and steam plants, great savings can be made by accurate knowledge of river flows and available plant capacities. This involves not only studies of all available data as to river flow in the past, but the forecasting of the future flows and the formulating of careful rule curves for the day to day operation of storage plants. Much careful study is being given to this by all large systems and what the subsidiaries of Southeastern Power and Light Company have done is only typical of the other companies. Messrs. J. P. Armero and D. M. Booth have, however, done some very interesting original work on this problem, which they describe as follows:

"In order that future operating conditions can be forecast as intelligently as possible, careful studies have been made of the hydrographs of all rivers involved over a period of not less than 25 years. From these studies a forecast hydrograph is drawn for the ensuing year. This hydrograph is determined in this manner:

"To obtain results with values of any proximity whatsoever to the actual hydrograph, the data of the rivers studied had to be treated as periodograms or curves representing functions which, although depending on cyclic variables, do not by themselves show a definite cyclic character. They are, in fact, cyclic functions whose periods are so long that the observations available cover but a small fraction of a cycle. The object of the periodogram analysis is to determine from the table of observations the equation of the curve, and with this to compute the values to be expected from the functions during the rest of the cycle. The periodogram is formed by the addition of a series of sinusoidal functions, and in some cases contains also lineal functions and constants. Generally, it is impossible to find the actual composition. Unless the observation covers at least one cycle, the problem is indeterminate. The indetermination is removed when a number of components is known, but even in such cases it is necessary for obtaining consistent results that the data be free from any error or perturbation. The results shown here in plotted form have been prepared by using a method whereby each component's period was estimated, and then computing their phase and amplitude. This method of attack is especially useful when observations, although not covering the whole cycle of the resultant, cover at least one cycle of each component.

"Fig. 3 shows the actual massed hydrograph and resultant curve obtained by the addition of the components found by the analysis.

"Fig. 4 shows the forecasted and actual hydrograph for 1926—Coosa River.

"Fig. 5 shows the forecasted and actual hydrograph for 1926—Tallapoosa River.

"This gives an idea of how closely the actual flow has followed the forecasted during previous years. Based upon studies of previous years flow, with consideration of wet, dry, average, or medium years, and with the aid of the study as mentioned above, rule curves are made up, covering the operation of the storage plants.

Figs. 6 and 7 show typical rule curves for the Georgia and Alabama storage reservoirs. The rule curves are followed very closely, and deviations are permitted only within certain limits, and to take care of unusual conditions on stream flow plants. Of course, occasionally there is insufficient rainfall to fill up the reservoirs along the rule curve. By following these curves, the various plants are operated in so far as possible at their most efficient points. Occasionally it is necessary to increase the load beyond the most efficient point to eliminate higher priced power during peak hours. By properly coordinating the operation of all plants on the systems, these occasions are rare.”

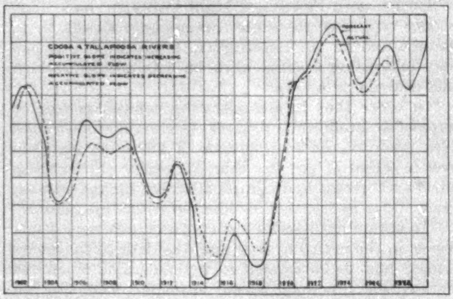

Fig. 3—Massed Hydrograph and Resultant Curve—Coosa and Tallapoosa Rivers

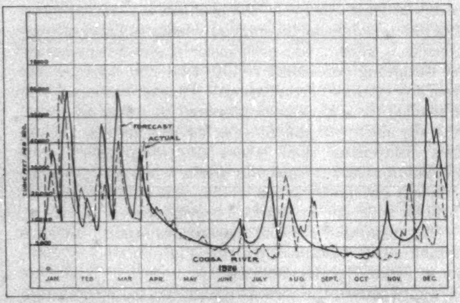

Fig. 4—Forecasted and Actual Hydrographs of Coosa River—1926

Operating and maintenance practise has also improved with the exchange of operating data and ideas. More careful maintenance schedules for all equipment are followed, thereby reducing maintenance cost and keeping all equipment in better and more efficient condition. This is particularly true of steam plants where all heavy maintenance work is done during the four normally inactive months of December, January, February, and March.

Tables I, II, and III show the effect in a system operating both steam and hydro plants of load growth and rainfall on production and operating costs of typical steam and hydroelectric plants.

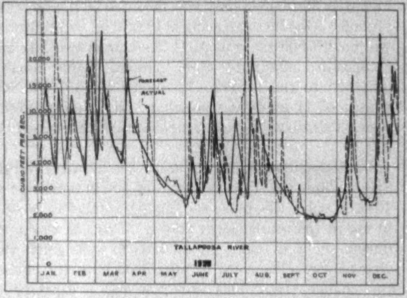

Fig. 5—Forecasted and Actual Hydrographs of Tallapoosa River—1926

At the present time the first 66,667 kv-a. unit of four which will ultimately be installed in a new mine mouth steam plant at Gorgas is now under construction. This plant, together with the existing steam plants and the big storage plants at Martin and on the Tallulah River, make possible the maximum use by both Georgia Power Company and Alabama Power Company of their run of river hydro plants. All combine to develop more kw. of capacity per dollar of investment and to produce more kw-hr. at a lower cost than would be possible under independent management. In a similar manner the Southern Power Company, the Carolina Power and Light Co., and Tennessee Electric Power Co.

TABLE I

PLANT PERFORMANCE—HYDROELECTRIC PLANT OPERATING IN A SYSTEM WITH STEAM PLANT

| Year | Output | Load factor | Maximum demand |
|---|---|---|---|
| 1923 | 153,094,600 | 29.4 | 69,500 |
| 1924 | 255,520,500 | 48.5 | 60,000 |
| 1925 | 227,387,000 | 44.0 | 58,500 |
| 1926 | 302,292,000 | 58.3 | 59,200 |
| 1927 | 291,880,000 | 56.7 | 58,000 |

OPERATION AND MAINTENANCE COSTS COMPARED

| Year | Unit cost in mills per kw-hr. | | |
|---|---|---|---|
| | Operation | Maintenance | Total |
| 1923 | .. | .. | 0.1553 |
| 1924 | 0.122 | 0.023 | 0.1450 |
| 1925 | 0.117 | 0.073 | 0.1900 |
| 1926 | 0.080 | 0.047 | 0.127 |
| 1927 | 0.074 | 0.131 | 0.205 |

*Maintenance unusually high in 1927 due to cost of welding runners.

TABLE II
COMPARISON OF YEARLY STEAM PLANT PERFORMANCE

| Year | Tons coal per year | Output kw-hr. | Load factor in per cent | Maximum demand kw. | Lb. coal per kw-hr. | Unit cost mills per kw-hr. | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Oper. | Maint. | Fuel | Total |
| 1920 | 118,159 | 88,088,100 | 20 | 45,000 | 2.56 | .. | .. | .. | 6.30 |
| 1921 | 137,763 | 112,000,600 | 25.6 | 55,000 | 2.46 | 0.81 | 0.57 | 4.92 | 6.30 |
| 1922 | 188,773 | 188,414,600 | 43 | 55,500 | 2.00 | 0.40 | 0.40 | 4.00 | 4.80 |
| 1923 | 145,184 | 145,250,200 | 33.1 | 54,600 | 2.00 | 0.52 | 0.95 | 4.00 | 5.47 |
| 1924 | 198,947 | 207,678,000 | 34 | 78,500 | 1.91 | 0.38 | 0.49 | 3.82 | 4.59 |
| 1925 | 334,196 | 350,795,400 | 54 | 78,800 | 1.90 | 0.32 | 0.40 | 3.80 | 4.52 |
| 1926 | 190,624 | 198,064,800 | 29 | 78,500 | 1.90 | 0.50 | 0.73 | 3.80 | 5.03 |
| *1927 | 263,807 | 276,553,800 | 46 | 75,000 | 1.90 | 0.34 | 0.52 | 3.80 | 4.66 |

*11 months only.
The cost of coal in the above figures is $4.00 per ton at the plant.

TABLE III
SOME MONTHLY PRODUCTION COSTS FOR A LARGE HYDROELECTRIC PLANT OPERATING IN SYSTEM WITH STEAM RESERVE PLANTS IN MONTHS OF DIFFERENT FLOWS

| | High flow | Medium flow | Low flow |
|---|---|---|---|
| Gross generation in kw-hr. | 38,474,600 | 16,505,800 | 9,250,200 |
| Station use kw-hr. | 119,600 | 103,500 | 115,900 |
| Net generation kw-hr. | 38,355,000 | 16,402,300 | 9,134,300 |
| Peak kw | 58,200 | 50,000 | 36,000 |
| Turbine hours | 2,221 | 1,600 | 1,297 |
| Operating cost | $ 2,270 | $ 1,840 | $ 1,745 |
| Labor | $ 1,654 | $ 1,524 | $ 1,534 |
| Material | $ 617 | $ 316 | $ 211 |
| Maintenance cost | $ 2,266 | $ 5,574 | $ 8,919 |
| Labor | $ 1,710 | $ 1,670 | $ 1,709 |
| Material | $ 556 | $ 3,904 | $ 7,210 |
| Production cost | $ 4,536 | $ 7,414 | $ 10,664 |
| Substation cost | $ 921 | $ 1,219 | $ 946 |
| Total payroll | $ 4,570 | $ 4,653 | $ 4,714 |
| Average number men | 43 | 46 | 46 |

Note: Maintenance during medium and low months includes contract expense shown under material for welding runners.

are working to the same end on their great systems.

The development of all the economical hydroelectric sites is not distant. The material improvement in steam generating efficiencies, together with the lowering plant costs, the reliability of the large steam units and the varying character of our southern streams are all making utility engineers in the south realize that a greater and greater proportion of power will be produced by steam in the future.

The extent and feasibility of interconnection and long distance transmission was thoroughly demonstrated in 1925 when over 600 mi. of line between Muscle Shoals in northwest Alabama and points north of Raleigh, North Carolina were linked up for several weeks and large blocks of power transmitted.

The year 1927, as far as Alabama and Georgia were concerned, was nearly as dry as 1925. Georgia had very little additional generating capacity and a very greatly increased load. Due to coordination of the systems, however, and the additional tie lines, water was conserved in the Burton storage all during the spring and drawn out in the late fall when most needed. Under independent operation the tendency would have been to have taken a chance on getting summer rains (which never came) and so to have drawn upon the stored water that when the final pinch came there would have been none left and then industries would have been forced to curtail because the tie lines could carry no more and the hydro plants would have been greatly reduced in capacity by lack of water. The accompanying load curves, Figs. 8, 9, and 10, and the rule curves, Figs. 6 and 7, demonstrate most clearly the value of unified operation of two large systems.

On December 3, 1927, systems from Chicago to Mobile and Pensacola were interconnected and thus over a thousand miles of transmission line and literally millions of kw. of generating capacity operated in parallel for some fifteen minutes. No power was interchanged but the availability of the interconnections in case of emergency was demonstrated.

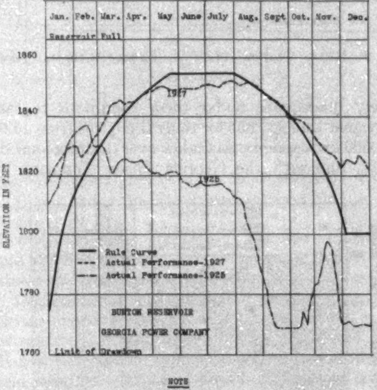

FIG. 6—RULE CURVE BURTON RESERVOIR—GEORGIA POWER COMPANY

In October 1927 a large cotton mill in Georgia had a failure in their isolated plant. Within twenty-four hours from the time notice was received, the Power Company has picked up over 3000 hp. of the mill's load and within seventy-two hours had picked up the entire 10,000 hp. This was only possible due to the capacity of two big interconnected systems, but it meant continued employment for several hundred people who would otherwise have been thrown out of work for two or three months.

In 1927 the Savannah River dropped to a flow nearly as low as in 1925. The local plant near Augusta was entirely inadequate under these conditions to carry the system load so that for several months from 15,000 to 20,000 kw. capacity was taken over the interconecting 110-kv. line with the Georgia Power Company and thus a curtailment of industry in a large territory entirely avoided.

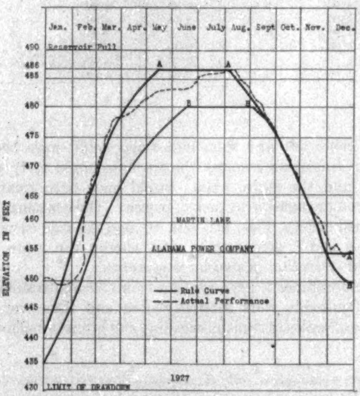

FIG. 7—RULE CURVE, MARTIN LAKE—ALABAMA POWER COMPANY

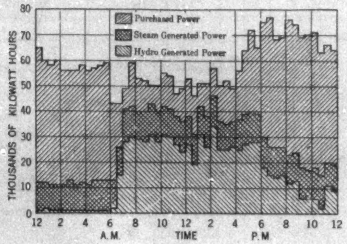

FIG. 8—GEORGIA POWER CO. LOAD CURVE OCT. 8, 1925

Another example of the greater use of available resources: Company A had available 25,000 kw. of transmission capacity but no surplus generating capacity and was interconnected on one side of its system with Company B, which had surplus power, and on the other side with Company C, which was short of power. Transmission facilities were leased from Company A, power purchased from Company B, and Company C's needs were completely taken care of.

The growth of each independent system, but even more the unified control of several systems, has promoted the use of larger power plants and larger generating units. When a system load is of the order of 400,000 kw. the annual growth will be 50,000 kw. at least; therefore, it is logical to install very large units. In the Buck steam plant, a powdered fuel plant, which the Southern Power Company recently put into operation, two turbo generators of 35,000 kv-a. each were installed. In the Martin Dam plant of Alabama Power Company three 37,500-kv-a. units were installed for an average head of 120 ft. At Jordan Dam (Lock 18), now under construction, four 29,000-kv-a. units,

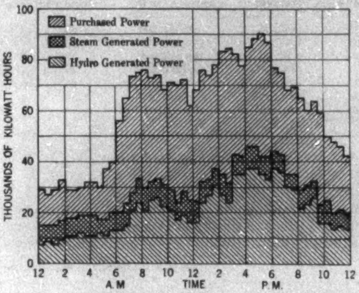

FIG. 9—GEORGIA POWER CO. LOAD CURVE NOV. 2, 1925

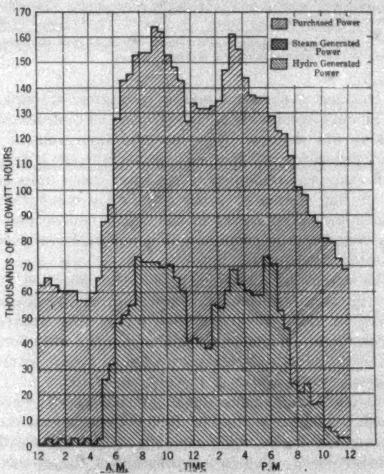

FIG. 10—GEORGIA POWER CO. LOAD CURVE SEPT. 28, 1927

operating at 93-ft. head, are being installed; at Upper Tallassee two 19,000-kv-a. units, operating at 55-ft. head will be in operation early in 1928. The Southern Power Company will have 45,000 kv-a. at its Oxford hydroelectric plant in service early in 1928. The High Rock Plant of the Aluminum Company of America was brought in in 1927 with 40,000 kv-a. The Southern Power Company will receive a large portion of the output of this plant over a new 40-mi. 110-kv. tie line. The Tennessee Power Company revamped their old Nashville steam plant, equipping two boilers for powdered fuel, and installing a 23,500-kv-a. turbine. Carolina Power and Light Co. late in 1926 brought in their Cape Fear Steam Plant with 30,000-kv-a. capacity and are now working on their Norwood hydro plant of 65,000-kv-a. capacity. The generators in this plant will be of the outdoor type. A third 17,500-kv-a. unit is now being added to the Bartletts Ferry Plant of the Columbus Electric & Power Company, bringing its capacity up to 52,500 kv-a.

When the new Gorgas steam plant of the Alabama Power Company was under discussion, very careful studies were made and 66,667 kv-a. units finally decided on as the most economical size for our conditions. This plant when completed will probably be the most economical plant in the Southeastern States. A brief description of this latter steam plant may be of interest.

The turbo generator is a 66,667-kv-a., 90 per cent power factor, 400-lb., 725-deg. fahr. machine arranged for four bleed points. The generator is cooled by four motor-driven blowers having a total capacity of 105,000 cubic feet of air per minute at a static pressure of 10 in. of water. The blowers drive the air through the generator air cooler in a closed system.

The condenser is 70,000 sq. ft., two pass, with 1-in. tubes, two circulating pumps, two condensate pumps, and one bank of air ejectors.

Two 30,000-sq. ft., 475-lb. pressure Babcock & Wilcox boilers and superheaters with Combustion Engineering Company Fin type water walls on three sides of the furnace are provided. Each boiler is guaranteed to produce a maximum of 450,000 lb. of steam per hr. at 475 lb., 725 deg. fahr. total temperature.

The boilers will be fired with pulverized fuel fed from a bin system. Three 15-ton mills discharge to cyclones and thence by conveyors to the pulverized fuel storage bin for each boiler. The single-line diagram, Fig. 11, shows the extreme simplicity of the electrical layout. This plant is expected to make a kw-hr. on the switchboard with 15,000 B. t. us. While many northern plants are more efficient thermally, this figured out the most efficient plant for this territory when the price of coal and the increased capital cost per kw. for greater efficiency were considered.

This plant plainly shows the rapid change in conditions in a few years and indicates the prime importance of careful study of load growth and of consideration of the improvement in efficiency of steam units. Whereas eleven years ago the first large unit installed at Gorgas was 25,000 kv-a., and the plant was built purely as a reserve steam plant to operate at from 10 to 25 per cent annual load factor, the new plant will be a base-load plant operating on a 50 per cent annual load factor at first and probably ultimately on a 70 per cent load factor. Another interesting fact is that while the new plant will be 50 per cent more efficient than the old, its cost per kw. will be but little, if any higher; such is the effect of larger units. Again, units of 66,667 kv-a. would not be the proper size were there not ample reliable tie lines between Alabama and Georgia so that such a unit would be available to both companies.

In present day practise all substations are of the outdoor type with steel girders or steel pole supporting structures. They are simple and sturdy with large clearances. Small control houses are built for the relay, protective and control equipment and telephones with a small storage space for spare parts that must be housed. In older substations the low-voltage buses and switches were put indoors, now for 11,000 volts or above nearly all are placed outdoors.

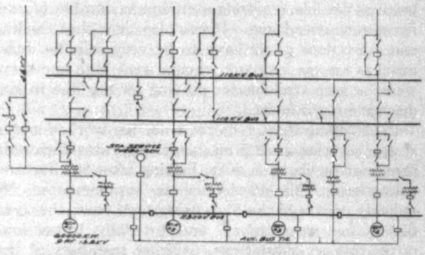

Fig. 11—Single-Line Diagram New 266,668-Kv-a. Gorgas Steam Plant—Alabama Power Co.

Double-circuit 110,000-volt lines and many single-circuit lines are built on steel towers but the majority of single-circuit 110,000-volt lines are of the familiar H-frame wood-pole type with one or two ground wires and with the structures guyed at frequent intervals. Chestnut, juniper, and cypress poles are frequently used, but by far the majority of lines are constructed with creosoted long leaf yellow pine poles. These make a splendid looking and a long lived, low maintenance cost, line.

By far the greater part of the territory served in the Southeastern states is sparsely settled with nothing like the density of load per sq. mi. that is encountered in the northeast or middle west. Therefore, types of construction have been developed which peculiarly suit these conditions. First cost must be kept at a minimum and at the same time operation and maintenance must be kept very low. A brief description of a typical line may be of interest. A single-circuit 110,000-volt line, 225 mi. long, from Mitchell Dam via Lock 18 to Hattiesburg, Mississippi. The total load was only about 12,000 kw., distributed at eight load centers. Prior to inauguration of hydroelectric service the more important of these load centers were supplied from local steam plants, and had good service, to which the hydroelectric service will of course be compared. Due to the small size of the various loads, it follows that the distribution organizations are small, and that there are therefore few men available for emergency patrols on the high tension line and substations. The redeeming feature about this territory was the fact that the prospects for growth in load looked very good. It has actually increased 2000 kw. in the last year.

While first cost had to be low, there had to be considerable spare capacity, at least in the line, to provide for future growth. It was also evident that the operating and maintenance costs must be comparatively low. To get low operating costs, it was evident that the line and connecting substations should be as nearly automatic as possible, requiring a minimum number of men in constant attendance. It was also clear that the line and substations would have to be very reliable, inasmuch as the service requirements were high and there were few men available for putting on the line to run down and repair faults.

In satisfying these requirements, we worked out a system covering the 225 mi., which operates with only three men regularly on duty, looking after the line and substations. This attendance is supplemented by monthly patrols of the line, using men from the local distribution organizations, and by daily inspections of the primary substations, utilizing members of the local supervisory organizations. These inspectors are, of course, supplemented by sending in our regular line and substation crews to do maintenance work when inspections indicate this to be necessary. Based on a comparison of the line design with that of existing lines, we do not expect an average of more than one major interruption per year on this line, and in general expect this to be of not over 7 or 8 hours' duration. There will, of course, be a number of momentary interruptions of one to two minutes' duration during the lightning season. One year's operation seems to be justifying our assumptions.

Considering the line construction, most of the distance the conductors are 397,500-cir. mil steel reinforced aluminum. Structures are of creosoted pine poles, 65 ft. high, with 8-in. tops, each structure being an H-frame consisting of 2 poles and a creosoted pine crossarm (6 in. by 8 in.), 32 ft. long. These structures are spaced on the average of a little over 1000 ft. apart. Insulators consist of 8 and 9 units for suspension and strain service. Poles are set approximately 7 ft. deep, and where soft ground is encountered, all structures are side guyed. In better ground, alternate structures are guyed. Galvanized tension rods are provided for bracing the cross arms, and tying them in with the tops of the poles. All hardware is grounded, there being two 4-lb. copper grounds per structure, one on each pole,—these terminating in ground pipes one in. in diameter and 8 ft. long. Two caps wires are provided which are of ⅝-in. Siemens Martin steel. These wires are insulated on 20,000-volt pin-type insulators, and serve a number of purposes. In the first place they stabilize the line mechanically, serving as head guys on each structure. They are also utilized in connection with a 500-cycle supervisory control system, to control certain substation switches and also motor operated switches which are placed at intervals of 15 mi. along the line, these being operated by the supervisory control system referred to, and power being supplied by small local 12-volt storage batteries. These cap wires are transposed at three points between sectionalizing switches and at sectionalizing switches, and are supplied with drainage units at sectionalizing switches and substations. They can therefore be used as an emergency communication system, and for this purpose are provided with drops at two-mile intervals which extend down the poles and terminate in small protective equipments, so that a patrolman can plug in a portable test set and secure communication with adjacent substations during line interruptions. These cap wires also terminate in telephone equipment at the various primary substations. Finally, being provided with drainage units and grounded through same, these cap wires serve as ground wires to some degree. We are satisfied they have considerable value in this respect, but as yet do not know just how effective they are as compared with the ordinary ground wire.

Considering next the substations, these are as near automatic as they can be made without going to undue complications. A typical substation consists of a tap on the 110 kv. line, with air break switches on each side, coming to an air break switch in the substation. Following this switch, which ordinarily is supervisory controlled, there is a 110-kv. fuse. Following the fuse are the transformers, which are in all cases out of door and self-cooled. It will be noted that no 110-kv. arresters were provided, as our experience indicated that on these small substations it is good economy to omit them. From the transformers, connections go to a double, low-voltage bus, the voltage being 44 kv. in some cases and 11 kv. in others. The various transformer and feeder switches are equipped with various relays, depending upon service required, and wherever possible, they are automatically reclosing. At three of the substations, Lock 18, Demopolis and Meridian, 110-kv. oil circuit breakers are provided in the main line; these, in the case of Lock 18 and Demopolis, being provided with CZ relays and automatic reclosers. At Meridian and Hattiesburg, synchronous condensers are installed which are fully automatic and provided with various protective relays, so that they will take care of themselves during line interruptions. Communication is provided along this line by means of antenna-coupled carrier-current sets, which are installed at all substations. In practically all cases these sets are remote controlled from the nearest city office, which in most cases is several miles away. As mentioned before, emergency communication between substations in case of line interruptions is provided by the cap wires.

The only substations along the 225-mi. of line where men are regularly on duty are at Lock 18, Meridian, and Hattiesburg. At Meridian a man is necessary because this is a dispatching point. His presence is made further advisable by the synchronous condenser installed. The condenser at Hattiesburg makes it advisable to maintain a man at this point also.

Transmission lines still constitute the weakest link in the chain between generating station and customer. The question of ground wires is still a mooted one but the majority of southern operators, after from 15 to 20 years' experience, feel sure that they are justified on important lines and afford material protection against lightning. The new 154-kv. lines being built in Alabama and Georgia are being over-insulated, but the equipment is not. For its protection, a weak link will be put in the lines near the substations by leaving off two or three of the insulator disks. On the question of high-voltage lightning arresters opinion is much divided. On the Southeastern Power and Light Co. system we feel that in the more important stations the transformers should be given the benefit of the doubt and arresters installed. Routine annual testing of transmission line insulators is now carried out by most companies. Some use a megger but the majority use the buzz-stick method. This has proved very satisfactory in eliminating defective insulators. Between the improvements in design and the elimination of defectives by various tests, the number of insulators punctured or destroyed by lightning is very few, nothing like the number we lost 10 years ago. It is still the general practise to patrol lines on foot at regular intervals with emergency patrol after every interruption.

With the growth and interconnection of systems the necessity of uninterrupted communication circuits has grown in importance. Important stations and load dispatching centers are usually coupled by several private land-line circuits as well as by Bell system lines wherever possible. In the last two years extensive use has been made of the carrier-current telephone system, and exceptionally good results have been obtained. On the Southeastern Power and Light Co. system carrier-current sets are now being installed in Atlanta and Birmingham in the load dispatchers' offices to permit immediate communication between load dispatchers on the two systems; also, for the purpose of intercompany commercial calls. They are being used regularly for load dispatching on over 1000 mi. of transmission lines. An accurate check was kept of the calls for 75 days, and 86 per cent of them were completed. The failure to complete most of the remaining calls was due to the operator called being where he could not hear the signals.

Oil circuit breakers continue to be one of the most important factors affecting satisfactory long distance transmission and system interconnection. Here again the increase in capacity of transmission lines and the concentration of power necessitate ever increasing capacity in the oil circuit breaker. Today short circuits of 1,000,000 kv-a. are possible in the Birmingham District substation and of 750,000 kv-a. at Atlanta. The additional tie lines between Alabama and Georgia will cause a complete change in 110-kv. oil switches in all of the Atlanta district oil switches. The general layout of the Southeastern Power and Light Co. system is such that we believe we shall continue to give best service by operating on so-called solid ties as compared to the loose link method, and limiting short circuits by opening it up at certain predetermined points. Later we shall probably add 110-kv. reactors through which normally no current flows. In contrast to this the Southern Power system operates to much better advantage on the loose-link coupling. Because of lack of sufficient data on the performance of high-capacity oil circuit breakers under full rating, a group of five large utilities formed about two years ago an Informal Committee on Cooperative Oil Circuit Breaker Tests. The breakers to be tested were bought by the interested companies and tested under actual system operating conditions. Manufacturers' representatives were invited to be present when their switches were tested. Much important information was gained and we feel that definite improvements in design have resulted directly or indirectly from these tests. As the Alabama Power Company's part, tests were made during 1926 and 1927 on six 44-kv. breakers of four different manufacturers and one 110-kv. breaker.

To summarize: The past four years have witnessed a growth by all utilities in the southeast. Additional and higher capacity interconnections have been made. Individual system operation has been improved as has coordination between systems. More use is being made of interchange facilities. More careful forecasts of load growth are being made and more careful system planning to handle such growth is being done. Advantage is being taken of the lower costs of larger units and particularly of the improvement in efficiency of the modern steam generating plants. Long distance transmission is growing more reliable.

But there are still many problems unsolved or only partially solved. Load dispatching grows more difficult and complicated with the growth of systems. From the standpoint of protection to service proper relaying will continue to require much study. The division of load between parallel circuits, the control of wattless current, system stability, and more reliable oil circuit breakers are problems worthy of the best engineering brains in the industry. As hydroelectric stations decrease in size, more automatic ones will be constructed to keep down the cost per kw-hr. The future will probably see still larger steam plants with larger units located at the mine mouth, when water is available there, and others as near to large load centers as available condensing water will permit. These will, in turn, bring up the problems of still heavier main trunk transmission lines operated at higher voltages than at present generally used in the southeast. The last word has not yet been said regarding lightning protection. Improvement in communication circuits also offers a fertile field for study.

If the record of the industry for continued reduction in cost per kw. and per kw-hr. is to be maintained and, at the same time, the service carried farther and farther afield to thinner and thinner territory, there is no danger of our engineers running out of work.

## Discussion

For discussion of this paper see page 408.

# Some Aspects of Pacific Coast Interconnections

BY P. M. DOWNING[1]
Member, A. I. E. E.

*Synopsis.—This paper tells in general of the reasons for, and the advantages of, interconnection between power supply systems. It enumerates five essential factors which must be considered in successful operation of interconnected systems; namely, (1) dependable communication; (2) centralized authority and control over operations; (3) location and isolation of trouble; (4) voltage regulation and control over the entire system; and (5) frequency control. A description is given of the interconnections along the entire Pacific Coast.*

* * * * *

INTERCONNECTION, as that term is used when applied to the electrical industry, means nothing more nor less than the pooling of the production and distribution facilities supplying power within a given area. It differs from transmission in that interconnection implies the transfer of energy from one system or area having a surplus to another system or area having a shortage, whereas transmission implies the transfer of energy from the point of production over a considerable distance to the point of usage.

Electric service was once local in character but with the advent of higher voltages, which made possible the transmission of power over greater distances, communities which theretofore had been supplied from local generating plants found it to their advantage to interconnect with other adjoining systems as a most logical and common sense way of making a more beneficial use of existing facilities.

Interconnection does not necessarily imply capital consolidation of the power supply systems involved. There are many instances where two or more independent systems are operating very successfully under contracts or working agreements that permit of economies not possible under separate operation. Very often, however, all of the advantages to be had from the interconnection are not obtained under contractual arrangements, due to the lack of sufficient flexibility in the contracts or working agreements in effect. To obtain maximum economic and beneficial results from interconnection, control and management should be unified. If power is to be distributed under the most favorable conditions, more than anything else there must be local territorial monopoly. No state, however richly endowed with water power, coal, oil, or other fuel, can make maximum beneficial and economic use of its facilities without interconnection.

At various times we hear of "giant power" and "superpower" systems. While these fascinating phrases probably make a stronger appeal to the imagination of the lay mind than does the more homely and commonplace expression "interconnection," aside from the generally accepted idea that giant power implies state or federal ownership, they mean substantially the same as does interconnection and all seek to accomplish the same end.

Some of the more enthusiastic proponents of giant power have gone so far as to suggest that there should be high-voltage lines of large capacity connecting different power-producing and power-using areas within the radius of practical electrical transmission, thus in effect producing a single pool of power into which all generating stations would deliver power and out of which all distributing systems, irrespective of ownership, would take delivery of such amount as they would need. From an idealistic standpoint such an arrangement would probably be well nigh perfect, but from a practical and economic standpoint the investment in transmission facilities would probably be so great that the purpose sought to be accomplished would be defeated.

Some of the more important advantages to be gained by the interconnection of two or more different power-supply systems are the following:

1. Greater reliability of service and increased economies. In case of a shortage of power due to accidents to equipments, other similar equipment on the interconnected system can supply the shortage until repairs are made or other units put into service. Under normal conditions, the more efficient units can be operated, the less efficient being held in reserve and operated only in emergencies.

2. Increased diversity, thus reducing the power requirements of the combined systems and by improving the load factor, reducing the capital investment in plant facilities.

3. Common use of reserve or spare capacity, thus further reducing the capital investment in plant.

4. In cases where the network is supplied with power from both steam and hydro sources, the hydro stations can be operated continuously at full load when water is available, thus making a maximum beneficial use of water power and a minimum use of steam. On a smaller system there would be much less opportunity of doing so.

5. General availability of power over large areas, thus making it possible for factories to locate where raw material, labor, market conditions, etc., are most favorable. This is particularly important as it permits manufacturing plants to locate in smaller towns and agricultural areas and use labor normally employed

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[1] Vice-President Pacific Gas & Electric Co., San Francisco, Calif.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Feb. 13-17, 1928.*

during certain seasons only. In this way interconnection becomes an active force in the decentralization of population.

Although there are many arguments in favor of interconnection as a most logical means of effecting economies, the extent to which power systems can be advantageously interconnected has certain limitations beyond which there is no advantage in going. Since the economies of interconnection lie in improved load factor, higher diversity, and greater use of existing facilities that is possible by combining loads of dissimilar character, it naturally follows that no great advantage would be gained by the interconnection of two or more systems unless by so doing these elements could be improved.

Obviously, there would be no advantage, economic or otherwise, in making any considerable investment in facilities necessary to interconnect two or more systems supplying different areas if those systems had similar power supply and load characteristics unless such interconnections would give a combined load of higher diversity, better load factor, improved service or one that would permit of a more general use of existing facilities.

Unfortunately, the wide-spread discussion of this subject that has taken place during recent years has given the public the impression that it would be practicable to interconnect all of the power systems in the country irrespective of the distances at which they might be separated, and, by parallel operation and exchange of power, effect economies to a point where the cost of power to individual consumers might be reduced. Nothing could be further from the fact. In the light of our present knowledge of the art, the advantages of interconnection are regional in character and limited to a radius of 300 to 400 miles.

Interconnection between various sources of electric generation and distribution on the Pacific Coast was the inevitable result of environment and economic pressure and became a reality almost immediately after the possibility of transmitting considerable quantities of power over long distances at high voltages had been fully demonstrated.

In California, where perhaps more has been done in the way of unifying the ownership and operation of electric utilities than has been accomplished elsewhere, topography was an important factor in bringing the systems together. In the eastern part of the State, running north and south for hundreds of miles, are the Sierra Nevada Mountains, having hydro resources amounting to approximately 9,000,000 hp. In the extreme western part of the state lie the cities with markets for large blocks of electric power. Between the two are the wonderfully fertile agricultural valleys which, of necessity, had to be crossed by the transmission lines carrying power from the hydro plants in the mountains to the cities on the coast. The result of such a situation was the construction of a number of transmission lines converging toward the cities as a common point of delivery. Later, by a natural process of consolidation, various systems were united into larger units which were in turn interconnected, thus forming a network of lines which permits of a ready exchange of power between areas supplied from a system under a single ownership and management or among several systems under separate ownerships and managements.

The powerhouses and transmission lines in California as shown on the accompanying map can all be interconnected to form a single network covering the entire state. Ordinarily there are three major connected groups. The first includes: California-Oregon Power Company, Pacific Gas and Electric Company, Snow Mountain Water and Power Company, City and County of San Francisco, Utica Mining Company, Coast Counties Gas and Electric Company, Truckee River Power Company.

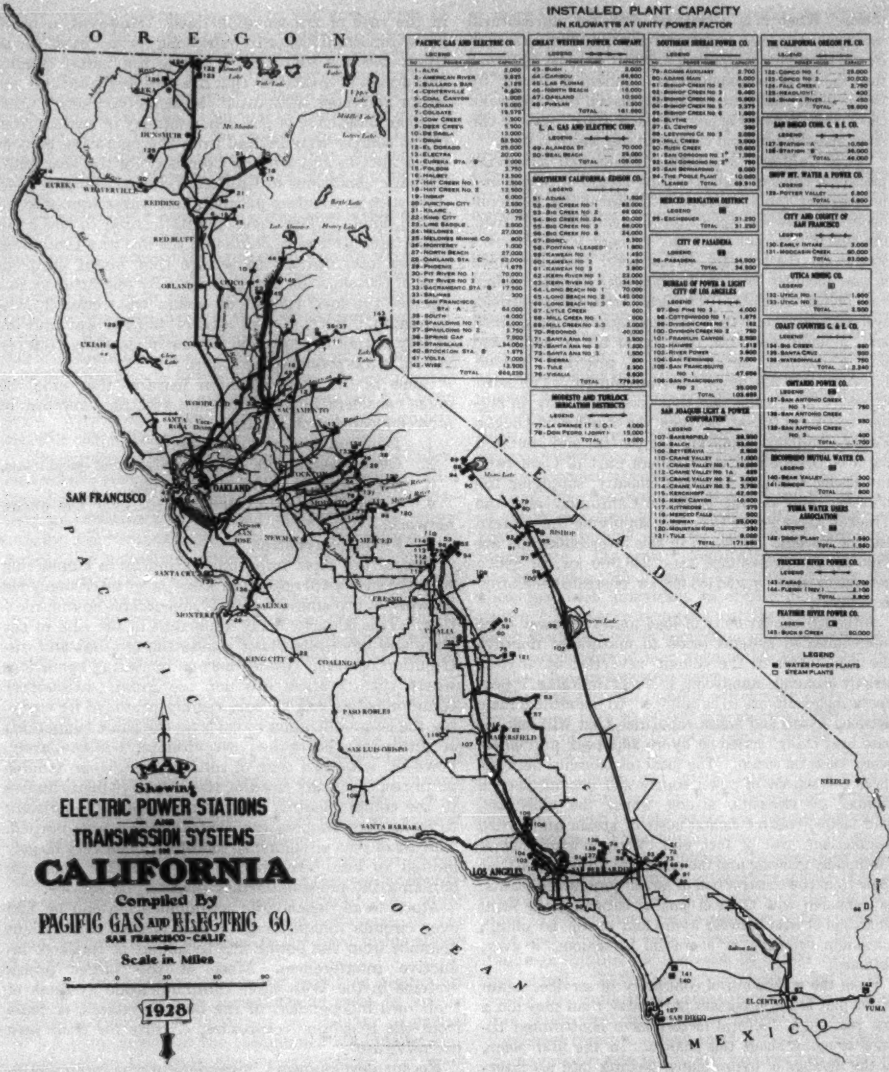
The second: Great Western Power Company of California, San Joaquin Light and Power Corporation, Merced Irrigation District, Feather River Power Company.

The third: Southern California Edison Company, Southern Sierras Power Company, City of Pasadena, Bureau of Power and Light, City of Los Angeles, San Diego Consolidated Gas and Electric Company. (See Fig. 1.)

Along the route of these transmission lines, running from the hydro plants on the western slope of the mountains to the larger cities along or near the coast were many smaller cities, towns, and agricultural communities. Some of these were supplied with power from small isolated plants, while others were without electric service. These small plants were inefficient and the opportunity to shut them down and obtain hydro power from transmission sources at less than it was costing to produce it locally was welcomed by all. At the same time the load thus obtained afforded a ready and quick revenue to the transmission systems. As a result of these mutual advantages, practically all of the isolated plants were abandoned very shortly after power was available from transmission sources. Eventually most of these small plants, together with the distributing systems, were taken over by the larger companies and became a part of a larger and more extensive network.

The agricultural areas were greatly benefited by the extension of these transmission lines. California is essentially an agricultural state, having a wet season and a dry one. Its semi-arid climate necessitates irrigation during the summer months and in certain localities at the lower elevations reclamation pumping is necessary during the winter months. By installing step-down transformers at various points, electric power was made available for both of these uses.

Some indication of the extent to which electric power is being used for agricultural purposes may be obtained



MAP Showing ELECTRIC POWER STATIONS AND TRANSMISSION SYSTEMS IN CALIFORNIA

Compiled By PACIFIC GAS AND ELECTRIC CO.
SAN FRANCISCO-CALIF.

1928

INSTALLED PLANT CAPACITY
IN KILOWATTS AT UNITY POWER FACTOR

**PACIFIC GAS AND ELECTRIC CO.**

| No | Power House | Capacity |
|---|---|---|
| 1 | Alta | 2.000 |
| 2 | American River | 5.825 |
| 3 | Bullard's Bar | 6.125 |
| 4 | Centerville | 6.400 |
| 5 | Coal Canyon | 1.000 |
| 6 | Coleman | 15.000 |
| 7 | Colgate | 19.575 |
| 8 | Cow Creek | 1.500 |
| 9 | Deer Creek | 5.500 |
| 10 | De Sabla | 13.000 |
| 11 | Drum | 52.500 |
| 12 | El Dorado | 25.000 |
| 13 | Electra | 20.000 |
| 14 | Eureka Sta. "B" | 9.000 |
| 15 | Folsom | 3.750 |
| 16 | Halsey | 12.500 |
| 17 | Hat Creek No. 1 | 12.500 |
| 18 | Hat Creek No. 2 | 12.500 |
| 19 | Inskip | 6.000 |
| 20 | Junction City | 2.500 |
| 21 | Kilarc | 3.000 |
| 22 | King City | 75 |
| 23 | Lime Saddle | 2.000 |
| 24 | Melones | 27.000 |
| 25 | Melones Mining Co | 800 |
| 26 | Monterey | 1.000 |
| 27 | North Beach | 27.000 |
| 28 | Oakland, Sta. "C" | 62.000 |
| 29 | Phoenix | 1.675 |
| 30 | Pit River No 1 | 70.000 |
| 31 | Pit River No 3 | 61.000 |
| 32 | Sacramento Sta. "B" | 17.500 |
| 33 | Salinas | 300 |
| 34 | San Francisco Sta. "A" | 64.000 |
| 35 | South | 4.000 |
| 36 | Spaulding No 1 | 6.000 |
| 37 | Spaulding No 2 | 3.750 |
| 38 | Spring Gap | 7.500 |
| 39 | Stanislaus | 34.000 |
| 40 | Stockton Sta. "B" | 1.875 |
| 41 | Volta | 7.000 |
| 42 | Wise | 12.500 |
|  | Total | 666,250 |

**GREAT WESTERN POWER COMPANY**

| No | Power House | Capacity |
|---|---|---|
| 43 | Bush | 2.000 |
| 44 | Caribou | 66,600 |
| 45 | Las Plumas | 65.000 |
| 46 | North Beach | 16.000 |
| 47 | Oakland | 10.500 |
| 48 | Phelan | 1.500 |
|  | Total | 161.600 |

**L. A. GAS AND ELECTRIC CORP.**

| No | Power House | Capacity |
|---|---|---|
| 49 | Alameda St | 70.000 |
| 50 | Seal Beach | 35.000 |
|  | Total | 105.000 |

**SOUTHERN CALIFORNIA EDISON CO.**

| No | Power House | Capacity |
|---|---|---|
| 51 | Azusa | 1.800 |
| 52 | Big Creek No 1 | 82.000 |
| 53 | Big Creek No 2 | 66.000 |
| 54 | Big Creek No 2A | 80.000 |
| 55 | Big Creek No 3 | 68.000 |
| 56 | Big Creek No 8 | 24.000 |
| 57 | Borel | 9.300 |
| 58 | Fontana (Leased) | 1.800 |
| 59 | Kaweah No 1 | 1.450 |
| 60 | Kaweah No 2 | 1.450 |
| 61 | Kaweah No 3 | 3.800 |
| 62 | Kern River No 1 | 23.000 |
| 63 | Kern River No 3 | 34.500 |
| 64 | Long Beach No 1 | 70.000 |
| 65 | Long Beach No 2 | 145.000 |
| 66 | Long Beach No 3 | 80.000 |
| 67 | Lytle Creek | 600 |
| 68 | Mill Creek No 1 | 600 |
| 69 | Mill Creek No 2-3 | 3.000 |
| 70 | Redondo | 40.000 |
| 71 | Santa Ana No 1 | 3.900 |
| 72 | Santa Ana No 2 | 1.800 |
| 73 | Santa Ana No 3 | 1.500 |
| 74 | Sierra | 800 |
| 75 | Tule | 2.300 |
| 76 | Visalia | 6.600 |
|  | Total | 779.390 |

**MODESTO AND TURLOCK IRRIGATION DISTRICTS**

| No | Power House | Capacity |
|---|---|---|
| 77 | La Grange (T. I. D.) | 4.000 |
| 78 | Don Pedro (Joint) | 15.000 |
|  | Total | 19.000 |

**SOUTHERN SIERRAS POWER CO.**

| No | Power House | Capacity |
|---|---|---|
| 79 | Adams Auxiliary | 2.700 |
| 80 | Adams Main | 5.000 |
| 81 | Bishop Creek No 2 | 5.800 |
| 82 | Bishop Creek No 3 | 6.480 |
| 83 | Bishop Creek No 4 | 5.900 |
| 84 | Bishop Creek No 5 | 3.375 |
| 85 | Bishop Creek No 6 | 1.600 |
| 86 | Blythe | 335 |
| 87 | El Centro | 390 |
| 88 | Leevining Ck. No 3 | 2.000 |
| 89 | Mill Creek | 3.000 |
| 90 | Rush Creek | 10.600 |
| 91 | San Gorgonio No 1* | 1.300 |
| 92 | San Gorgonio No 2* | 750 |
| 93 | San Bernardino | 8.000 |
| 94 | The Poole Plant | 10.000 |
|  | *Leased Total | 69.910 |

**MERCED IRRIGATION DISTRICT**

| No | Power House | Capacity |
|---|---|---|
| 95 | Exchequer | 31.290 |
|  | Total | 31.290 |

**CITY OF PASADENA**

| No | Power House | Capacity |
|---|---|---|
| 96 | Pasadena | 34.500 |
|  | Total | 34.500 |

**BUREAU OF POWER & LIGHT CITY OF LOS ANGELES**

| No | Power House | Capacity |
|---|---|---|
| 97 | Big Pine No 3 | 4.000 |
| 98 | Cottonwood No 1 | 1.875 |
| 99 | Division Creek No 1 | 162 |
| 100 | Division Creek No 2 | 750 |
| 101 | Franklin Canyon | 2.500 |
| 102 | Haiwee | 1.812 |
| 103 | River Power | 3.600 |
| 104 | San Fernando | 7.000 |
| 105 | San Francisquito No 1 | 47.656 |
| 106 | San Francisquito No 2 | 35.000 |
|  | Total | 103.685 |

**SAN JOAQUIN LIGHT & POWER CORPORATION**

| No | Power House | Capacity |
|---|---|---|
| 107 | Bakersfield | 26.950 |
| 108 | Balch | 33.000 |
| 109 | Betteravia | 2.500 |
| 110 | Crane Valley | 1.000 |
| 111 | Crane Valley No 1 | 16.000 |
| 112 | Crane Valley No 1A | 425 |
| 113 | Crane Valley No 2 | 3.000 |
| 114 | Crane Valley No 3 | 3.750 |
| 115 | Kerckhoff | 42.000 |
| 116 | Kern Canyon | 10.000 |
| 117 | Kittredge | 375 |
| 118 | Merced Falls | 500 |
| 119 | Midway | 25.000 |
| 120 | Mountain King | 350 |
| 121 | Tule | 6.000 |
|  | Total | 171.650 |

**THE CALIFORNIA OREGON PR. CO.**

| No | Power House | Capacity |
|---|---|---|
| 122 | Copco No 1 | 25.000 |
| 123 | Copco No 2 | 30.000 |
| 124 | Fall Creek | 2.750 |
| 125 | Headlight | 400 |
| 126 | Shasta River | 450 |
|  | Total | 58.600 |

**SAN DIEGO CONS. G. & E. CO.**

| No | Power House | Capacity |
|---|---|---|
| 127 | Station "A" | 10.000 |
| 128 | Station "B" | 36.000 |
|  | Total | 46.000 |

**SNOW MT. WATER & POWER CO.**

| No | Power House | Capacity |
|---|---|---|
| 129 | Potter Valley | 6.800 |
|  | Total | 6.800 |

**CITY AND COUNTY OF SAN FRANCISCO**

| No | Power House | Capacity |
|---|---|---|
| 130 | Early Intake | 3.000 |
| 131 | Moccasin Creek | 80.000 |
|  | Total | 83.000 |

**UTICA MINING CO.**

| No | Power House | Capacity |
|---|---|---|
| 132 | Utica No. 1 | 1.900 |
| 133 | Utica No. 2 | 600 |
|  | Total | 2.500 |

**COAST COUNTIES G. & E. CO.**

| No | Power House | Capacity |
|---|---|---|
| 134 | Big Creek | 690 |
| 135 | Santa Cruz | 900 |
| 136 | Watsonville | 750 |
|  | Total | 2.340 |

**ONTARIO POWER CO.**

| No | Power House | Capacity |
|---|---|---|
| 137 | San Antonio Creek No 1 | 750 |
| 138 | San Antonio Creek No 2 | 550 |
| 139 | San Antonio Creek No 3 | 400 |
|  | Total | 1.700 |

**ESCONDIDO MUTUAL WATER CO.**

| No | Power House | Capacity |
|---|---|---|
| 140 | Bear Valley | 300 |
| 141 | Rincon | 300 |
|  | Total | 600 |

**YUMA WATER USERS ASSOCIATION**

| No | Power House | Capacity |
|---|---|---|
| 142 | Drop Plant | 1.560 |
|  | Total | 1.560 |

**TRUCKEE RIVER POWER CO.**

| No | Power House | Capacity |
|---|---|---|
| 143 | Farad | 1.700 |
| 144 | Fleish (Nev.) | 2.100 |
|  | Total | 3.800 |

**FEATHER RIVER POWER CO.**

| No | Power House | Capacity |
|---|---|---|
| 145 | Buck's Creek | 50.000 |

LEGEND
■ WATER POWER PLANTS
□ STEAM PLANTS

FIG. 1

from the fact that the more than 35,000 irrigation pumping installations in this state represents a greater number than is to be found in all of the other states combined. But pumping is not the only use made of electric power by these agricultural communities. This is evidenced by the fact that of the almost 1,700,000 electric consumers in the state, approximately 300,000 or 20 per cent are outside of incorporated cities and towns. When it is considered that the agricultural business is the least remunerative of any that is served by the supplying companies, it will at once be apparent that the rural communities have benefited greatly by the fortunate fact that nature has placed them between the source of power supply in the eastern part of the state and the principal market in the western part.

While California is generally recognized as having pioneered the long distance transmission of power and pointed out the advantages of maintaining interconnections between systems supplying adjacent territory, the field of interconnection has not been limited to this state. On the contrary, it has been extended until it now includes Oregon, Washington, Nevada, Idaho, and British Columbia. Physical connections between systems operating in these various states are maintained and, if found desirable, they could all be connected into a common network. As a practical matter, however, this has never been attempted. The most extensive interconnection that is continuously in regular operation is that between the California-Oregon Power Company, supplying the central and southern parts of Oregon and the northern part of California, the Pacific Gas and Electric Company, supplying the northern and central parts of California, and the Truckee River Power Company supplying the western part of Nevada. Involved in this interconnection are 4760 mi. of high-voltage lines, 546,000 kw. of hydro generating capacity, and 183,000 kw. of steam generating capacity.

Although the diversity of load found on most large interconnected systems tends to materially improve the load factor of the system, nevertheless, from a strictly economic standpoint, it is still desirable, if best operating results are to be obtained, to maintain a ratio between hydro and steam capacities that will call for base load being carried on hydro and peak and emergency loads on steam. The ideal relationship between these two sources of power supply will depend upon a number of elements, among which the chief are, load factor, relative capital costs of steam and hydro installations, cost of fuel, etc. With a load that is continually growing and the economic advantages that come from the construction of larger generating plants, as compared with those of smaller capacity, the ideal allocation of load between hydro and steam to obtain maximum economy of operation is seldom, if ever, obtained.

From the standpoint of continuity of service, steam plants play a less important part today than they did a few years ago. Several factors have contributed toward bringing about this change. In the first place, as the number of hydro plants feeding into an interconnected network is increased, temporary cessations of operation of one or more generating stations whose output represents a comparatively small percentage of the total have but little effect on the general service of the system as a whole. A similar situation obtains in the case of transmission lines. However, a much more important factor in improving service in so far as transmission is concerned is due to the better quality and design of insulators that are now available and the better and more substantial physical construction used.

Some indication of the dependability of service from hydro sources may be had from the operating records of Pacific Gas and Electric Company for the year 1927. Climatic conditions in California during the past year were such as to afford an abundant water supply at all hydro plants. The steam plants located in the more important cities were floated on the line as a protection against interruptions to service that might occur in case of transmission line trouble. By operating in this manner the load carried on steam was reduced to a minimum. With a peak load of 439,568 kw. and an energy output of 2,380,000,000 kw-hr. less than 0.9 per cent of it was produced by steam.

Some of the more essential features that must be given consideration in connection with the operation of interconnected systems are:

1. Dependable communication,
2. Centralized authority and control over operations,
3. Location and isolation of trouble,
4. Voltage regulation and control over the entire network,
5. Frequency control.

One of the most important adjuncts in connection with the successful operation of any large interconnected network of transmission lines is dependable communication. This is particularly important in the case of the large and more important generating stations and distribution centers. Under normal operating conditions where the distances are not too great, satisfactory communication can be very readily provided by carrying the communication circuits on the same supporting structures that carry the power circuits. Unfortunately, however, with this type of construction, when trouble occurs on the power circuits, the inductive disturbances to the communication circuits are generally sufficient to make them inoperative when they are most needed. The use of such circuits has, therefore, been very largely limited to local and routine service rather than for handling the more important dispatching service.

Much more dependable communication can be had over circuits independent of and located a sufficient distance from the power line to be out of range of inductive interferences. Most of the larger power systems in the West have communication systems of their own independent of the power systems, or lease from the telephone companies, circuits for their own exclusive use.

Recent developments in carrier-current radio equipment give promise of providing a cheaper and more dependable means of communication between different stations on a transmission network than any other now available. This method of communication differs from ordinary broadcasting in many respects. First, the carrier current is superimposed on the power lines at a frequency below that used by regular broadcasting stations, thus avoiding any interference of one with the the other. Second, it can be installed on any voltage power line and is not materially influenced by switching, short circuits, or other transient disturbances on the power circuit. Third, in the case of long lines the first cost of the installation is less than that of a metallic circuit. Fourth, it has all of the flexibility of a metallic system.

The most recent installation of this kind is that on the Pacific Gas and Electric Company's 220- and 110-kv. lines running between the hydro plants on Pit River and the load dispatcher's office in Oakland, a distance of approximately 240 mi. Although couplers have not yet been installed around the transformers used for stepping the voltage down from 220,000 to 110,000 volts, communication between stations at the extreme ends of these lines is better and during the few months the system has been in operation the service has been more dependable than that over an independent metallic circuit running between the two places.

The success attending the operation of large interconnected networks is due in a very large measure to the fact that authority and control over the details of operation are centralized in the load dispatcher. In emergencies his authority is supreme. To successfully handle the important duties of this position calls for good judgment, resourcefulness, a thorough and complete detailed knowledge of the entire systems, but more important than anything else. the ability to think quickly and act with decision when trouble occurs. So important is this position that service from an interconnected network may be good or bad depending on whether the dispatching is handled well or otherwise. Allocation of load among the various generating substations and over the different lines in a way that will make a maximum beneficial use of the more efficient plants or equipment conserve water or fuel and at the same time be prepared to meet any operating emergency that might arise, are some of the more important responsibilities of this position. Under normal operations, these conditions can be met without any great difficulty but once the regular operating routine is upset by storms, breakdowns, water shortage, or otherwise, the resourcefulness of the load dispatcher may be taxed to the limit in his efforts to maintain service.

Where generating stations and switching centers are separated by distances sometimes as great as several hundred miles, there is always the liability of partial or complete failure of the communication circuits connecting into the load dispatcher's office. To meet emergencies of this kind, dispatching orders are generally designated by code numbers. By referring to them in this manner, the time required to issue the order is reduced to a minimum. Also the liability of mistakes occurring where orders have to be repeated one or more times before reaching the station to which it is issued, is also minimized.

Localizing and isolating troubles that might be serious enough to interrupt or impair service over a considerable area is another big problem that comes up in connection with the successful operation of an interconnected network. At one time this was more or less a matter of guess work. Practically all switches were manually operated. Such instruments as were available were less reliable than those of today and were not designed to indicate the direction of trouble from where they were installed. Alert attendants, expert at guessing correctly the location of trouble and having the athletic ability to open the right switch in the shortest possible time, were therefore greatly in demand. Present day equipment has materially simplified this situation. Automatic overload, low-voltage, reverse current, time limit, reclosing, and other similar relays have almost entirely superseded manual operation in modern up-to-date installations. The almost uncanny dispatch and precision with which these devices function has brought about a greatly improved service and, by reducing man power, a much more economical service.

As an interconnected network grows and the amount of power delivered into it increases, the necessity of having dependable switches becomes of increasing importance. The construction of high-voltage switches has been materially improved during recent years, but there has been practically no change in the general design. Failure to keep pace with the development of other facilities used in connection with the production and transmission of high voltages has made them the weakest link in a power system.

The first attempt to build switches for operation at voltages as high as 60,000 was made in 1899 by the engineers of the Bay Counties Power Company, now a part of the Pacific Gas & Electric Company's system. The consolidation and interconnection of a number of smaller systems soon made it apparent that switching could no longer be done on the low voltage side of the transformers. The manufacturers had not yet developed switches for this voltage. To meet a situation precedent to the giving of satisfactory service from an interconnected network, it was necessary for the company to design and build its own high-voltage switches. The first attempts were necessarily crude. Entrance bushings suitable for operation at 60,000 volts could not be had. To further increase the electrical factor of safety, the conductors leading through these bushings into the switch contacts were heavily insulated with varnished cambric. Such small porcelain bushings as were available were mounted in well seasoned wood tops and the oil containers were ordinary fiber or pressed paper washtubs. The three legs of the switches were insulated from each other and from the ground.

Improvements in the design and manufacture of bushings have to a very considerable extent eliminated the inflammable material used in the original design and present day switches are much more rugged and dependable than those of 25 years ago. Although these improvements have added to the mechanical and electrical efficiency of the equipment, they have also increased their first cost to a point where, with the usual number of air switches for by-passing and cutting out the oil the high-voltage switch equipment in a modern generating plant represents an investment equal to 50 per cent of that in transformers.

No other piece of electrical equipment offers greater opportunity for improvement than do high-voltage switches. This is becoming more and more apparent as voltages increase. The very satisfactory operation of the two 220,000-volt lines in California has proved beyond question the practicability of going to even higher voltages just so soon as the economics of the situation warrant. What the future may bring forth in the way of improvements in high-voltage switches remains to be seen. Thus far the vacuum type switch has given more promise of relief than any other that has been proposed. Laboratory tests have shown that there is practically no deterioration or damage to the contacts after opening a 15,000-volt circuit carrying 120 amperes more than 500 times. If this type of switch can be developed to a point where it can be used on a commercial basis, there is every reason to believe that it will rapidly supersede the present oil type.

If electric utilities fulfill their obligations to serve the public, they must be able, ready, and willing to supply at proper rates any kind or character of load that may be offered them. Much of the load on a general power supply system will be of low power factor and unless a consumer is penalized because of the low power factor of his load or is offered some inducement in the form of reduced rates or otherwise to warrant his providing the necessary facilities for improving it there will be a considerable amount of wattless current on the system that will have to be taken care of somewhere.

This may be carried on one or more generating stations to suit operating conveniences or a much better plan, and one that becomes absolutely necessary as the length and voltage of the transmission lines increase, is to install synchronous condensers at or near the distribution centers of the system. The number and capacity of such installations will depend on the voltage of the system, the load characteristics, the permissible variation in voltage, etc., but whatever capacity may be needed to give proper service under normal operating conditions, it is very desirable, if satisfactory service is to be given under abnormal conditions, to have a reasonable margin of spare capacity to maintain adequate service in emergencies.

Condenser installations can be fully justified not only as a most satisfactory means of improving voltage regulation but they also have a tremendous economic value in that by improving the power factor, the amount of power that can be carried over a given line is materially increased.

Speed control on an interconnected system is a comparatively simple matter. Irrespective of the number, size, or location of generating stations, one station does the governing. Local conditions determine which one can best perform this function. Ordinarily the station near the load center, where a sufficient governing margin can be maintained at minimum cost, is selected. Where a hydro plant does the governing it is desirable that one having sufficient forebay capacity to supply the varying drafts necessary to meet load fluctuations be selected. Where the network is supplied from both hydro and steam sources, especially where the latter is operated as a standby or reserve source of power supply there is but little, if any, economy in governing with steam. Maximum economy will be obtained by loading all hydro plants except the one doing the governing, thus reducing the steam load to a minimum and keeping hot only enough boilers to pick up the predetermined amount of load that is to be thus protected against interruptions in case of trouble.

To prevent see-sawing of load between different plants, the governors on the governing plant are adjusted sensitive enough to operate on a minimum variation in speed. Those on the other plants are adjusted to operate only on the wider variations that would occur if and when for any reason they might become separated from the governing station.

On a reasonably large interconnected network of lines, carrying a highly diversified load, the instantaneous variations in load or what is ordinarily called the governing margin is comparatively small. In fact it is not at all unusual during short water periods to reduce this to practically zero and follow the gradual variations in load by hand control. On the system of Pacific Gas and Electric Company, with a peak of almost 440,000 kw-hr. supplied to an area larger than any other interconnected network in the West, the normal governing margin is between 1000 and 2000 kw.

## Discussion

For discussion of this paper see page 408.

# Interconnection and Power Development
## in Chicago and the Middle West

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***Synopsis.**—The development of power stations in the Chicago District is described, showing how small stations have been replaced, and the energy supply for light, power, and traction consolidated by the use of high-voltage lines.*

*The interconnections between stations and the developments of recent years and for the immediate future are outlined. This includes cables at 66,000 and 132,000 volts, with circuit capacities of 60,000 kv-a.*

*A station in central Illinois, near the coal supply, is being tied in with the Chicago District.*

*Interchange of energy between companies is conducted under an agreement, which is an important factor in the success of interconnection. Some of the operating problems are outlined briefly.*

THE development of power producing equipment for the supply of electrical energy in utility service during the past quarter of a century has been greatly influenced by the development of electrical transmission of energy which has accompanied it.

The ability to send energy economically from a principal point of production to numerous points of distribution was the prime factor in a period of development in which many small pioneer stations were replaced by a few larger power stations, with a considerable gain in economy of construction and operation.

A sketch of the course of power station development in the Chicago District, which is typical of progress in general in this respect, may serve to illustrate some of the phases of this period of growth.

### POWER DEVELOPMENT IN CHICAGO

At the time the pioneer turbine-driven units were being planned for installation at the Fisk Street Station in 1901-2 in the Chicago District, there were from 10 to 12 power stations supplying electricity, 12 power stations supplying trolley and elevated train service at 600 volts d-c., a total of 24 power stations generating electricity chiefly for use in a local area. Only two of these stations supplied power to areas outside the radius of direct economical distribution from the point of production, because transmission at higher voltages by cables was yet in its infancy.

The year 1903 marked the inauguration of service at the Fisk Street Station at a generator voltage of 9000, chosen to make it available for transmission to substations, from which local distribution was effected.

The former generating stations being centers of distribution naturally formed the nucleus of this development, and lines to these points formed the first interconnections, since the stations were continued in operation for peak-hour purposes for some years before being abandoned.

The production of energy at Fisk Street Station was attended by a material reduction in the investment per kilowatt of plant capacity, and this opened the way for the economical supply of energy for electric transportation service which followed.

Thus, when rehabilitation of the equipment of the surface car lines followed the granting of new traction franchises in 1907, the additional power required was purchased and delivery was made over transmission lines to converter substations, whence 600-volt energy could be economically distributed.

The former cable car service, which had required 10 separate power houses, was converted to electric cars and these sources of power were abandoned, throwing this load to the electricity supply stations.

Similar unification of power supply took place in the suburban areas.

Within 10 years from the time the first turbine station went into service, the total number of power stations in Chicago and its suburbs had been reduced from 24 electric and 10 cable power stations to not more than 9 or 10 stations in all. Of these, five were producing the major part of the energy, the others being retained for use during peak-hours only.

The merging of traction supply with general light and power load approximately doubled the load on the supply systems and made it possible to use turbo generator units much larger than would have been chosen if the power supply of the district had not been thus unified and consolidated.

This advantage was by no means small, as the total turbo generator capacity installed during the first decade of this development amounted to about 275,000 kw. in three generating stations, whereas the total capacity in the 24 electric stations in service in 1903 did not much exceed 100,000 kw.

Progressive increases in the capacity of units were made as rapidly as the manufacturers could work out the problems involved, and the following tabulation of the maximum sizes of units and the year in which they came into service is of interest:

| Year first put into service | | Maximum size of turbo generator |
|---|---|---|
| 1903 | Vertical | 5,000 kw. |
| 1906 | " | 8,000 " |
| 1908 | " | 14,000 " |
| 1912 | " | 20,000 " |
| 1913 | Horizontal | 25,000 " |
| 1915 | " | 30,000 " |
| 1917 | " | 35,000 " |

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Development was retarded for a few years by the events of the World War, but active growth was resumed in 1919 and in the Chicago District, in the middle western states, and indeed throughout the United States, proceeded at an unprecedented rate.

The accelerated growth from 1919 on necessitated a complete readjustment of power station development programs in all large centers of population, and necessitated the choice of still larger units and station capacities in the Chicago District.

For example, the Calumet Station in South Chicago was planned in 1919, on a pre-war basis, for six 30,000-kw. units, with the expectation that this would care for the requirements of growth in that District for perhaps 10 years. But, as a matter of fact, it had to be developed to full capacity in the second year, after the first unit went into service; that is, the sixth and last unit went into service in about four years, after construction was started on the first unit.

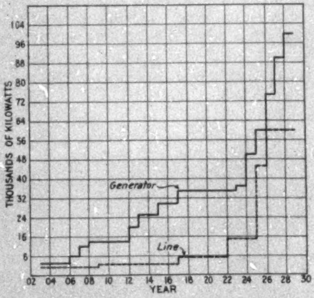

FIG. 1—LARGEST UNIT IN SERVICE, CHICAGO DISTRICT

The construction of the Crawford Avenue Station followed immediately upon the completion of the Calumet Station, and the first two units, of 50,000- and 60,000-kw. capacity respectively, went into service in the fall and winter of 1924-5.

Subsequent installations in service and under construction at Crawford Avenue Station follow: (Fig. 1)

| | | |
|---|---|---|
| 1925 | Unit No. 3 | 50,000 kw. rated capacity. |
| 1926 | Unit No. 4 | 75,000 kw. rated capacity. |
| 1927 | Unit No. 5 | 90,000 kw. rated capacity. |
| 1928 | Unit No. 6 | 100,000 kw. rated capacity. |

The chart, Fig. 2, giving annual increments of maximum load in the City of Chicago, illustrates the demands for service which necessitated such a program of installation of power station capacity.

In the suburban area, outside the limits of the city of Chicago, a similar process of consolidation of generating capacity, and elimination of smaller and less efficient stations was in process from 1912 on.

To supply the northerly suburban area stations were constructed at Waukegan, some 30 mi. north of the Chicago city limits, at Blue Island, about two miles southwest of the city limits, and at Joliet, some 33 mi. southwest of the city. These stations supplied towns in the valley of the Illinois River and elsewhere in that section of the State, at 33,000 volts.

These lines served to interconnect the Blue Island and Joliet Stations, and, in later years, the Joliet Station was interconnected with the station at Peoria.

The Waukegan Station, being located on a large site where water from Lake Michigan is available for condensing purposes, has been developed as one of the larger stations of the interconnected Chicago group. It has a capacity of 110,000 kw., the third unit of 50,000-kw. capacity having been put into service in 1927.

Similar developments took place in other parts of Illinois and in the neighboring states.

## DEVELOPMENT OF INTERCONNECTION

The use of interstation tie-lines has been in general practise since power station development reached a point where two stations under the same management were located in such proximity as to make interconnection practicable.

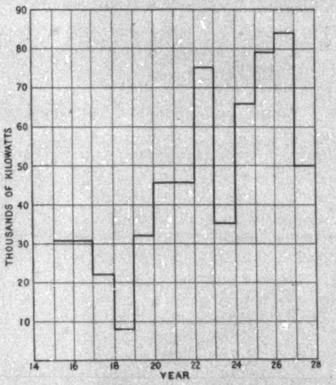

FIG. 2—ANNUAL INCREASE SYSTEM MAXIMUM, CHICAGO

Such interstation lines were operated at the voltage of the generator. Later, the voltage used for transmission of the supply of energy to substations was more often employed.

Interconnections of this type were of relatively small capacity until the size of generator units became such that an excessive number of circuits was required to provide an adequate reserve for the larger units.

In the Chicago District such interconnections were established between the Fisk Street and Northwest

Stations, a distance of about eight miles, at 12,000 volts.

Other interconnections were made between stations in suburban districts at 33,000 volts, with overhead lines forming a part of the general transmission system.

These interstation lines were however, of minor importance when compared with the transmission capacities necessitated by the rapid growth of the past 10 years.

The Calumet Station was located at South Chicago, 13 mi. southeast of the Fisk Street Station, to provide a supply of energy for the great industrial district in that section of Illinois and Indiana. However, the unexpectedly rapid development of load made it necessary to transmit a considerable part of the energy produced there to the Fisk Street zone. This called for a group of lines having a capacity of the order of 100,000 kv-a., and, since these must be underground cables, it was very desirable that the capacity of individual cable units be as great as it was practicable to secure at that time from manufacturers of cables.

This was accomplished by the selection of a 33,000-volt, three-conductor cable unit, having a capacity of 15,000 kv-a., and these cables became the first link in a chain of interstation lines of high capacity, which have been installed since 1921 between all of the principal generating stations in the Chicago District.

Unfortunately the development of "ionization" phenomena interfered with operation of some of these cables at 33,000 volts after about a year, and they were reduced to 22,000 volts, with, of course, a corresponding reduction in capacity.

When the Crawford Avenue Station went into service, cables forming a part of the 22,000-volt system were converted into a tie-line between that station and Fisk Street, and other cables were laid to Northwest Station as well.

From Northwest Station a 33,000-volt cable of foreign manufacture was laid northward to Evanston to interconnect with 33,000-volt overhead lines of the Public Service Company of Northern Illinois. This formed an interconnection between Northwest Station and the Waukegan Station, some 30 mi. north of the Chicago city limits, and this cable has continued to operate at 33,000 volts without serious trouble.

In 1924 it became apparent that the use of a much higher voltage would be necessary for overhead tie-lines to secure the required line capacity, and the first of a system of steel tower lines on private right-of-way, operated at 132,000 volts, was constructed from Calumet Station to the Joliet Station, and to the Gary steel-making district in Northern Indiana. A little later this was extended to Michigan City, some 50 mi. east of the Chicago city limits.

Following the extension of this line to Michigan City, a connection was completed from that point to the Twin Branch Station of the Indiana and Michigan Electric Company, near South Bend, Indiana.

This was the first interconnection from the affiliated group of Chicago systems to one of outside ownership and is, at present, used to receive energy from Twin Branch for use in the Gary-Hammond District. It is also available as reserve to the Indiana and Michigan Electric Company when necessary.

From Twin Branch, other lines extend east to Ohio, and thence to West Virginia and Pennsylvania. It was through this interconnection that the paralleling of a group of systems reaching eastward to Massachusetts was accomplished (for a few minutes) some months ago.

Continuous parallel operation of the Chicago District with the Ohio system is fairly stable when more than 10,000 kv-a. is being transferred from one system to the other.

More recently, parallel operation was carried on for over an hour with the Ohio system, while it was tied in with lines extending through West Virginia, Tennessee, and Georgia to Pensacola, Florida. The fluctuations were not greater at the Chicago end than under normal operation with the Ohio system only.

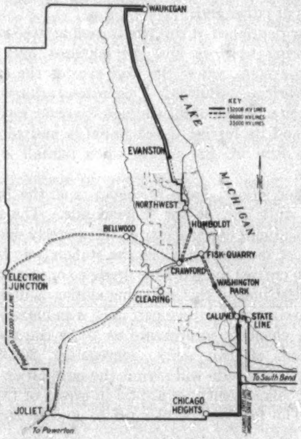

Fig. 3—Interconnection Chicago District, 1929

Sufficient experience has been had to make it apparent that when the weaker links have been increased to be comparable with the stronger, these systems can be operated in parallel successfully for such periods of time as may be necessary to meet the needs of operation during emergency transfers of energy.

### Current Developments

In view of the rapid absorption of the ultimate capacity available at the Crawford Avenue site, where six of the 10 ultimate units will have been installed within five years, sites have been acquired at points on the shore of Lake Michigan for future power development (Fig. 3 ).

The first of these to be developed was Waukegan, 40 mi. north of the center of Chicago, and about midway between Chicago and Milwaukee, where three units, aggregating 110,000 kw., are now in service, and building has been provided for a fourth unit of 50,000 kw. rating.

This station is connected to Chicago by a 132,000-volt line, with a capacity of 60,000 kv-a., which is overhead from Waukegan to the Chicago city limits; thence to Northwest Station it is underground. This six-mile link of 132,000-volt cable is one of two pioneer installations put into service in 1927, the other being in the city of New York.

There is also a 132,000-volt overhead line, from Waukegan to Milwaukee, which acts as a reserve to the systems at either end.

Power developed at this site is used as needed in the neighboring territory and the northern part of the Chicago system, where the load exceeds the capacity of the Northwest Station. This latter station is dependent upon a branch of the Chicago River for condensing water, and its further development is limited by the sluggish flow of this stream when rainfall is below average.

Another site on Lake Michigan is at the Indiana-Illinois state line, on the Indiana side. The city of Chicago adjoins this property on the westerly side.

Most of the land on which the station is to be built has been created by hydraulic dredging operations.

The first unit of this state line station is under way and is to consist of a three-part unit, with high-and low-pressure elements so arranged as to be the operating equivalent of two units, aggregating 208,000-kw. capacity. This site will permit the installation of five units of this capacity, or a total in excess of 1,000,000 kv-a. The first unit is planned to go into service in 1929.

This station will be unique in the Chicago District, in that all of its energy will be transformed to higher voltages and sent to other zones for distribution and utilization.

Approximately half of the output of the first unit will be sent into the city of Chicago, and the remainder into northern Indiana and Illinois, outside of Chicago.

Energy sent into Chicago will be carried by underground cables having a capacity of 60,000 kv-a. per circuit at 66,000 volts.

Energy sent into the outlying territory will be carried by overhead lines at 132,000 volts, and to the neighboring cities of Hammond and East Chicago at 33,000 volts.

Within the city of Chicago, the use of 66,000-volt cables for transfer of large blocks of energy between stations was adopted in 1926, and several such lines have been in satisfactory service for more than a year between Crawford Avenue Station and the Fisk Street and Northwest Stations.

A new type of distribution center, receiving energy at 66,000 volts and distributing it at 12,000 volts in blocks of 4000 to 8000 kv-a., has been developed as a means of decentralizing the amounts of energy concentrated at generating stations on 12,000-volt busses.

These distribution centers will have an initial transformer capacity of 120,000 kv-a., and will distribute ultimately, about 200,000 kv-a. each. Being located midway between generating stations, they will effect economies in 12,000-volt cable which will offset other costs and result in a net saving in investment.

The first of these distribution centers, to be known as Washington Park, will come into service in 1928, and will be located midway between the Fisk Street and Calumet Stations on the south side of the city.

In Chicago and vicinity, the interchange of energy between power stations for the winter of 1928-9 at the peak hour is graphically depicted in Fig. 4.

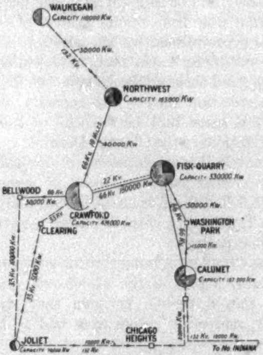

FIG. 4—POWER INTERCHANGE AT PEAK HOURS, CHICAGO DISTRICT, 1928

In this chart, the load in the station zone is indicated by the shaded portions. Where the zone load is greater than the station capacity, the overload is indicated by cross-hatching. The area of the circles is proportionate to the capacity of the respective stations.

Rights-of-way have been secured for overhead lines at 132,000 volts, connecting Joliet with Crawford Avenue Station, and for an outer belt line between Joliet and Waukegan, to be constructed as load conditions may make their installation advantageous.

Much discussion and calculation has centered about the idea that energy should be produced at points near to coal mines, and sent thence by high-voltage lines to the electricity market, instead of sending the fuel to stations located in the districts where the electrical energy is produced.

In the Chicago District, the major part of the fuel supply is brought from mines 200 mi. or more distant, and the problem of delivering hundreds of thousands of kw. of energy by overhead transmission lines at such distances is by no means simple.

Coupled with that problem is the one of finding a place where a supply of water for condensing purposes is present, as well as a supply of coal.

In Central Illinois, a location has been found which approximates this combination.

The Illinois River has a flow which is maintained in dry seasons largely because of the water supplied from Lake Michigan through the Chicago Drainage Canal. This river flows southwest from Joliet and passes to the west of the coal fields in central Illinois.

A site has been chosen on the Illinois River, about 14 mi. southwest of Peoria and some 70 mi. northwest of the coal fields, from which the major supply of coal used in Chicago power stations is taken. A direct railroad connection from mines to this site has been provided.

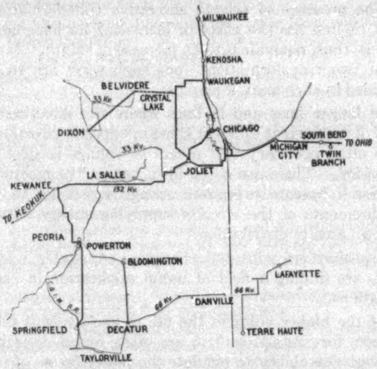

Fig. 5—Powerton District, 1928

This site has been named "Powerton," and is now being developed for two units of 55,000 kw. each, the first of which will go into service in the fall of 1928, (Fig. 5).

This station is to be operated by a separate company, whose business will be the generation of energy, which will be taken by the utilities serving the neighboring cities, such as Peoria, La Salle, Ottawa, Springfield, and Decatur. The remainder will be delivered to the Joliet District of the Public Service Company of Northern Illinois, and perhaps, at times, to the southwestern part of the city of Chicago.

The development of an economical station in this locality not only provides for future growth in this part of Illinois, but will effect large savings in fuel and operation cost, by producing energy now generated in smaller and, for the most part, much less efficient stations. Most of these stations will be shut down, except for the peak-hour shift.

The energy delivered to the cities north and east of Powerton will be transmitted by overhead lines at 132,000 volts.

Nearby cities will be supplied by connecting into the 33,000-volt system of lines now used for bulk supply in that part of the state, and through an overhead, 66,000-volt system to Springfield and cities easterly therefrom.

### Basis of Operation

The use of reserve generating capacity and low-cost energy to the fullest practical extent is facilitated in the Chicago District by the provisions of a three-party interchange energy agreement, which pools reserve capacity and permits the flow of energy to neighboring zones whenever the load in the immediate zone permits; or when the energy so transferred costs less than that produced in the neighboring zone.

The difference between the total capacity in the pool and the coincident maximum load of the three systems is taken as the group reserve (until a higher maximum has been established, or additional capacity put into service).

The percentage of group reserve is taken as the standard and any company having a reserve percentage higher than the group percentage is compensated for the carrying charges on its excess station capacity, by the other company or companies whose percentage of reserve is less than that of the group. This permits the smaller companies to install larger units than would be possible if only the requirements of their individual systems were to be met, and thus gives them capacity for future growth at a lower investment cost, with higher operating efficiency.

This is not accomplished at the expense of the larger companies (except temporarily), as they are able to draw upon the excess capacity thus created and so defer, for a year or more, additions to their own plants.

The program of power station construction for the entire district is coordinated through a committee of two representatives from each company, which studies load increases in the various zones, and recommends to the executives the size and location of units to be added from year to year, their recommendation being made about two years in advance of the dates when the units are to come into service.

This committee also has a subcommittee of load dispatchers, which meets weekly to arrange operating schedules for the transfer of energy from the more efficient stations to other zones at off-peak hr., to arrange a coordinated program of turbine outages for overhauling purposes, and, in emergencies, to confer by telephone and arrange relief where it may be required.

The conditions, as they existed in one of the summer months of 1927, will serve to illustrate the way in which the interchange energy agreement is accomplishing the result contemplated by the parties thereto.

| Company | A | B | C | Total kw. |
|---|---|---|---|---|
| System maximum....... | 864,300 | 139,800 | 44,700 | 1,041,000 |
| Reserve capacity, kw..... | 101,245 | 97,980 | 2,075 | 201,300 |
| Reserve quota (19%)..... | 165,875 | 26,240 | 8,585 | 201,300 |
| Excess and *Deficiencies. | *64,630 | 71,740 | *6,510 | .. |

Company "A" paid Company "B" for 64,630 kw. of reserve capacity, and Company "C" paid Company "B" for 6510 kw. of reserve capacity. Thus, Company "B" was reimbursed for an excess of 71,740 kw. in its reserve capacity.

During the same month, Company "A" delivered to Company "B" 9,135,000 kw-hr., Company "B" delivered to Company "A" (in other zones) 16,936,000 kw-hr., and Company "A" delivered to Company "C" 9,172,000 kw-hr.

Of the total of 35,243,000 kw-hr. thus transferred, about 19,000,000 kw-hr. were delivered at off-peak hour, and resulted in a saving in fuel consumed of about $19,000.00 in that month.

The three systems are operated normally in parallel with each other and with the Twin Branch Station at South Bend, most of the time.

Parallel operation with the Milwaukee system is not normal, as this line is maintained, primarily, as a reserve connection for use in emergencies.

Interconnections with companies west and south of the Chicago District are also operated, for the most part, as reserve connections and are paralleled only as operating conditions require it. These lines are of small capacity and are not suitable for other than local reserve service.

### SUMMARY OF RESULTS

The interconnection of power stations by lines of relatively large capacity has resulted as follows:

a. the size of generating units is increased, while the total capacity and reserve for a district is decreased;

b. the investment per kw. of capacity in generating stations and the total investment is decreased;

c. the consumption of fuel is reduced by ability to give the more economical units the "base load" of an entire district;

d. the reliability of service is enhanced by increased availability of the capacity and reserve in generating units, during emergencies and routine operating work, such as overhauling and repairing equipment.

### PROBLEMS OF INTERCONNECTION

It has been apparent, from the foregoing recital of experience with plants in the Chicago District, that there are some problems which require solution before an interconnected group may realize the advantages sought: These problems relate, chiefly, to the ability to control the division of energy between neighboring stations and to make delivery continuously when occasion requires.

The experience in the Chicago District indicates that these problems lie outside of the generating equipment almost entirely, and relate to the size, voltage, length, and other characteristics of the interconnecting lines.

When line capacity is high, and lengths are short in proportion to the voltage of transmission, the transfer of energy between stations is readily accomplished by governor control of the generating units.

When lines are relatively long and have a capacity which is approached by the normal surges of synchronizing energy, which flow between the two sources of power, there is instability of operation, and lack of continuity is likely to result.

The presence of several successive transformations in a tie-line has the effect of increasing its impedance and is, thus, equivalent to an increase in length. More than two transformations (one each way) are to be avoided in such lines, if possible.

In longer lines and in lines where the direction of flow of energy is at different times in opposite directions, it is often necessary that means of voltage control be provided. These are required to permit the receiving station to operate its bus at a voltage level suited to the requirements of the circuits supplying energy within its own area of distribution.

Transformers with tap changers, adjustable under load, are finding a field of useful application in such situations.

At the higher voltages the use of synchronous condensers for voltage control are often found desirable through the ability to regulate the power factor of the system secured thereby.

These problems have been met and dealt with in those locations where long distances are involved, as in California hydroelectric systems, more than in the industrial centers of the Middle West; but continued development of longer lines in these states suggests the probability that the problems related to line characteristics will be an increasing factor in the developments of the next decade.

### CONCLUSION

In reviewing the foregoing discussion, the author finds a predominance of illustrative data taken from experience in the Chicago District and Illinois, which raise in his mind the fear that the scanty reference to the interconnection work done in other important cities of the Middle West has left the picture incomplete. His apology is, therefore, offered with the explanation that had he been able in the time at his disposal to familiarize himself with the experience in such centers as Detroit, St. Louis, and Cincinnati, he would gladly have made use of it to illustrate some of the aspects of the relation of interconnection to power development.

In conclusion, it has been shown that interconnection and power development have already been well coordinated in some of the large centers of population.

The coordination of major points of power production by interconnections in a group of states is under way.

The next decade will see a continuing development of large power stations, joined by lines of high-voltage of great capacity, coordinating the supply of energy to great areas, as has been done in metropolitan centers of population.

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20. *The Application of Relays for the Protection of Power System Interconnections.* L. N. Crichton and H. C. Graves, Jr., TRANS. A. I. E. E., Vol. 47, No. 1, 1928, p. 259.

Relay requirements for interconnected systems and new methods for protection against phase to phase and line to ground faults are discussed. A typical relay installation on a 220 kv. interconnection is described.

21. *The Conowingo Hydroelectric Project of the Philadelphia Company's System—With Particular Reference to Interconnection.* W. C. L. Eglin, see p. 372.

Important features of the Conowingo Project described. Relation between the Conowingo Project and the 220 kv. interconnection of the Philadelphia Electric Company, the Pennsylvania Power and Light Company, and Public Service Electric and Gas Company discussed, particularly with reference to economies involved.

22. *Progress and Problems from Interconnection in the Southeastern States.* W. E. Mitchell, see p. 382.

Growth of utilities in the Southeast described. Importance of unified operating and financial control in economic system planning and operation is stressed. Operating methods and problems are outlined and attention called to particular problems as yet unsolved. Present trend in power plant, line, and substation design and construction is discussed.

23. *Some Aspects of Pacific Coast Interconnections.* P. M. Downing, see p. 393.

Conditions necessary for economical interconnections are outlined. Unified control and management necessary for most economical operation. Major facts to be considered in operation of interconnected systems are described. The Pacific Coast interconnection is used to illustrate these points.

24. *Interconnection and Power Development in Chicago and the Middle West.* H. B. Gear, see p. 399.

Growth of power development and interconnection in the Chicago District is described and current developments outlined. Operation under the three party exchange agreement is discussed. Interconnection problems requiring solution are cited.

### INTERCONNECTION THROUGH FREQUENCY CHANGERS

25. "Frequency Converter Ties Between Large Power Systems." J. W. Dodge, *General Electric Review*, Vol. 26, June 1923, pp. 435-444.

The characteristics and field of application of the following types of frequency changer sets are discussed; (1) synchronous, (2) induction, (3) speed regulating-induction (Sherbius), (4) induction-synchronous (systems electrically tied through windings of induction end), and (5) synchronous converter.

26. *A 35,000-kw. Induction Frequency Converter.* O. E. Shirley, TRANS. A. I. E. E., Vol. 43, 1925, pp. 1011-1024.

Induction-synchronous set for New York System. Power interchange is possible in either direction. In addition to providing mechanical tie the set permits interchange of wattless between systems through windings of induction machine.

27. "35,000 Kw. Synchronous Frequency Changer Set." M. W. Smith, *Electric Journal*, Vol. 21, July 1924, pp. 343-346.

Description of straight synchronous set for Brooklyn Edison Company.

28. *The Use of Frequency Changers for Power System Interconnection.* H. R. Woodrow, TRANS. A. I. E. E., Vol. 44, 1925, pp. 369-371.

Considerations determining selection of 35,000 kv-a. synchronous type set for interconnection of 25 and 60 cycle systems of Brooklyn Edison Company. The pull out point (70,000 kv-a.) is sufficiently high for the systems to hold together on loss of largest 25 cycle unit (30,000 kv-a.).

29. "A 49,000 Kv-a. Frequency Converter Set." R. A. McCarty, *Electric Journal*, Vol. 23, July 1926, pp. 339-341.

Large synchronous set for Commonwealth Edison Company.

### INTERCONNECTION THROUGH TRANSFORMERS

30. *Voltage and Power Factor Control of 60,000 Volt Transmission Lines Connecting Two Generating Stations.* R. Bailey, TRANS. A. I. E. E., Vol. 40, 1921, pp. 995-1015.

Installation of three-phase induction regulators in combination with step-up transformers for voltage and power-factor control of 60 kv. tie lines. Ability of this type of equipment to withstand severe short circuits.

31. *Transformers for Interconnecting High-Voltage Transmission Systems; for Feeding Synchronous Condensers from a Tertiary Winding.* J. F. Peters and M. E. Skinner, TRANS. A. I. E. E., Vol. 40, 1921, pp. 1181-1191.

Discussion of special problems encountered in use of star connected three winding transformers and auto-transformers with tertiaries for interconnection.

32. *Performance of Auto-Transformers with Tertiaries Under Short Circuit Conditions.* J. Mini, Jr., L. J. Moore, and Roy Wilkins, TRANS. A. I. E. E., Vol. 42, 1923, pp. 1060-1068.

Tests on transformers with tertiaries described and results discussed. Capacity of tertiary windings is dependent on magnitude and duration of short circuit. The kv-a. capacity and reactance of tertiaries are interdependent.

33. *Theory of Three Circuit Transformers.* A. Boyajian, TRANS. A. I. E. E., Vol. 43, 1924, pp. 508-529.

Characteristics of three winding transformers, including auto-transformers with tertiaries. Discussion of general theory, regulation, division of load, impedance for short circuits, behavior in parallel with a two-circuit transformer, and characteristics under unsymmetrical loads.

34. "Three Winding Transformers." J. F. Peters, *Electric Journal*, Vol. 22, Jan. 1925, pp. 12-16; Feb. 1925, pp. 71-77.

Practical discussion of three winding transformer theory, with illustrative calculation of typical problems.

35. *Transformer Tap Changing Under Load.* H. C. Albrecht, TRANS. A. I. E. E., Vol. 44, 1925, pp. 581-586.

Comparison of the synchronous condenser, the transformer with load ratio control, and the induction regulator as a means of regulating voltage on interconnecting lines. Discussion of fields of application of the various methods, or combinations of methods.

36. "Tie-in Transformer Equipped with Load Ratio Control." M. H. Bates, *General Electric Review*, Vol. 28, Dec. 1925, pp. 823-826.

36,000-kv-a. three-phase auto-transformer for interconnection tie between Duquesne Light and West Penn Power Companies.

37. "Arrangements for Load Ratio Control." H. R. Wilson, *General Electric Review*, Vol. 29, May 1926, pp. 335-338.

Description of load ratio control arrangements employing parallel windings with ratio adjusters, and combinations of single or parallel windings with auxiliary regulating transformers of different types.

38. "Two 60,000 Kv-a. Load Ratio Control Transformer Banks for Philadelphia Electric Company." A. Palme and H. O. Stevens, *General Electric Review*, Vol. 29, Sept. 1926, pp. 634-638.

Combination of standard power transformers and three-phase regulating transformer equipments. Method is adaptable to existing installations where load ratio control is required.

39. "60,000 Kv-a. Transformer Banks Equipped for Change of Ratio Under Load." W. M. Dunn, *Electric Journal*, Vol. 23, August 1926, pp. 398-402.

Parallel winding type load ratio banks for interconnection between Philadelphia Electric Company, and Public Service Company of New Jersey.

40 (a). *Application and Design of Load Ratio Control Equipment.* A. Palme, JOURNAL A. I. E. E., Vol. 46, Nov. 1927, pp. 1202-1206; 1269-1273, (Discussion).

40 (b). *Transformer Tap Changing Under Load.* L. H. Hill, JOURNAL A. I. E. E., Vol. 46, Nov. 1927, pp. 1212-1221; pp. 1269-1273, (Discussion).

Applications for load ratio transformers are discussed in these two papers. Parallel winding, single winding, and regulating transformer types of load ratio control are described and discussed.

41. *Characteristics of Interconnected Power Systems as Affected by Transformer Load Ratio Control.* L. F. Blume, TRANS. A. I. E. E., Vol. 46, 1927, p. 590.

Comparison of voltage control by generator field with that by combination of generator field plus transformer load ratio control. Comparison of synchronous condensers and load ratio

control for voltage regulation. Voltage control in transmission line loops.

### STABILITY OF POWER SYSTEMS

42. *Some Problems in the Operation of Power Plants in Parallel.* E. C. Stone, TRANS. A. I. E. E., Vol. 38, Part 2, 1919, pp. 1651-1674.

Characteristics and capacity of transmission circuits for interconnecting power systems are discussed. Calculation of synchronizing power, the division of wattless, and means for eliminating excess circulating wattless current are described.

43. *Power Control and Stability of Electric Generating Stations.* C. P. Steinmetz, TRANS. A. I. E. E., Vol. 39, part 2, 1920, pp. 1215-1287; *General Electric Review*, Vol. 23, Aug. 1920, pp. 688-701, Sept. 1920, pp. 756-768.

Unstable condition on system of Commonwealth Edison Company in 1919 is analyzed. Effect of sectionalizing reactors on flow of synchronizing power and stability of the system. Formulas developed for calculation of synchronizing power transfer, low frequency power fluctuations and energy transfer, and armature and field transients in synchronous machines.

44. "Calculation of Synchronizing Power." E. S. Henningsen, *General Electric Review*, Vol. 24, Nov. 1921, pp. 951-956.

Defines synchronizing power and develops formulas for its calculation under following conditions; (1) constant bus potential, (2) constant magnetic flux in generators, and (3) constant field excitation.

45 (a). *Some Theoretical Considerations of Power Transmission.* C. L. Fortescue and C. F. Wagner, TRANS. A. I. E. E., Vol. 43, 1924, pp. 16-23; 71-103.

45 (b). *Power Limitations of Transmission Systems.* R. D. Evans and H. K. Sels, TRANS. A. I. E. E., Vol. 43, 1924, pp. 26-38; 71-103, (Discussion).

45 (c). *Limitations of Output of a Power System Involving Long Transmission Lines.* E. B. Shand, TRANS. A. I. E. E., Vol. 43, 1924, pp. 59-70; 71-103, (Discussion).

The preceding three papers present the results of analytical investigations of the power system stability problem. The applications of general circuit constants and the circle diagram to the problem is outlined and discussed.

46. "Analytical Solution of Networks." R. D. Evans, *Electric Journal*, Vol. 21, April 1925, pp. 149-154; May 1925, pp. 207-213.

Short circuit network calculations including determination of current in branches of power networks outlined. Discussion is paralleled by typical calculations.

47. *Power System Transients.* V. Bush and R. D. Booth, TRANS. A. I. E. E., Vol. 44, 1925, pp. 80-103.

Presentation of an analytical step-by-step method for calculation of power system stability under transient conditions.

48. *Fundamental Considerations of Power Limits of Transmission Systems.* R. E. Doherty and H. H. Dewey, TRANS. A. I. E. E., Vol. 44, 1925, pp. 972-984; 994-1003, (Discussion).

General discussion of the factors entering into the problem of power system stability.

49. *Transmission Stability.* C. L. Fortescue, TRANS. A. I. E. E., Vol. 44, 1925, pp. 984-994; 994-1003, (Discussion).

Behavior of a simple transmission system during steady load conditions, switching operations, sudden increase in load, and short circuits discussed and illustrated by angle diagrams. Presentation of problems of transient and static stability.

50. *Stored Mechanical Energy in Transmission Systems.* J. P. Jollyman, TRANS. A. I. E. E., Vol. 44. 1925, pp. 935-937.

Performance of stored mechanical energy in synchronous machinery connected to a transmission system during sudden changes in system conditions. A tabulation of typical flywheel effects is included.

51. *Calculation of Steady State Stability in Transmission Lines.* Edith Clark, TRANS. A. I. E. E., Vol. 45, 1926, pp. 22-41; 80-94, (Discussion).

Methods of calculating steady state stability by (1) the equivalent circuit, (2) the circle diagram, are presented with formulas and illustrative calculations.

52 (a). *Practical Aspects of System Stability.* Roy Wilkins, TRANS. A. I. E. E., Vol. 45, 1926, pp. 41-50; 80-94 (Discussion) and

52 (b). *Further Studies of Transmission Stability.* R. D. Evans and C. F. Wagner, TRANS. A. I. E. E., Vol. 45, 1926, pp. 50-80; 80-94, (Discussion).

Description of tests on the system of the Pacific Gas and Electric Company, with a comparison of calculated and test values obtained. The second paper presents, in addition, an analytical method for calculation of power system transients.

53. "Calculation of Single Phase Short Circuits by the Method of Symmetrical Components." A. P. Mackerass, *General Electric Review*, Vol. 29, April 1926, pp. 218-231; July 1926, pp. 468-481.

Discussion of method of symmetrical components for calculation of single-phase short circuits on three-phase networks, with illustrative examples.

54 (a). *Experimental Analysis of Stability and Power Limitations.* R. D. Evans and R. C. Bergvall, TRANS. A. I. E. E., Vol. 43, 1924, pp. 39-58; 71-103, (Discussion).

54 (b). *An Investigation of Transmission System Power Limits.* C. A. Nickle and F. L. Lawton, TRANS. A. I. E. E., Vol. 45, 1926, pp. 1-21; 80-94, (Discussion).

Experimental shop tests with commercial machines on miniature networks. Discussion of stability problem together with comparison of calculated and test results.

55. "Stability of Alternating Current Turbine Generators with Fluctuating Loads." John Strasser, *Electric Journal*, Vol. 23, Aug. 1926, pp. 413-420.

Development of a method for the determination of the stability of turbine generators at instantaneous overloads.

56. *Stability Characteristics of Alternators.* O. E. Shirley, TRANS. A. I. E. E., Vol. 45, 1926, pp. 1108-1115.

Alternator characteristics with (1) constant power output, (2) variable impedance, and (3) constant impedance, loads are discussed. A formula and series of curves for specifying limiting short circuit ratios of general purpose alternators are proposed.

57. "A Mechanical Analogy to the Problem of Transmission Stability." S. B. Griscomb, *Electric Journal*, Vol. 23, May 1926, pp. 230-235; see also Westinghouse Electric and Manufacturing Company Reprint 282.

Behavior of a typical power system under stable and unstable conditions as illustrated by a mechanical model.

58. "Review of Papers on Stability of Power Systems." Appendix to Westinghouse Electric & Manufacturing Company's Reprint 282.

Brief statement of scope of each of a selected list of twenty-one papers dealing with stability of power systems together with a very complete bibliography on this subject to January, 1927.

59. *Transients Due to Short Circuits.* R. J. C. Wood, L. F. Hunt, and S. C. Griscomb, TRANS. A. I. E. E., Vol. 46, No. 1, 1927, p. 68.

Results of stability investigation on system of California Edison Company 1925-1927. Majority of short circuits found to be single phase to ground. Factors affecting stability on this system (switch operation, fault reactance, fault resistance, load, etc.) are discussed.

60. *Static Stability Limits and the Intermediate Condenser Station.* C. F. Wagner and R. D. Evans, TRANS. A. I. E. E., Vol. 47, No.1, 1928, p. 94, (Discussion).

A method is developed for determining static stability of transmission systems with three or four synchronous sources. A special application is the stability problem with one or two intermediate synchronous condenser stations.

61 (a). "Stability Characteristics of Machines." R. D.

Evans and C. F. Wagner, *Electrical World*, Vol. 89, Jan. 15, 1927, pp. 141-143.

61 (b). "Quick Response Excitation for Alternating Current Synchronous Machinery." A. C. Powel, *Electric Journal*, Vol. 24, April 1927, pp. 157-162.

61 (c). "High Speed Excitation for Stability." *Electrical World*, Vol. 89, May 21, 1927, pp. 1061-1063.

These three articles discuss advantages of (1) low generator reactance in reducing system phase angle, (2) quick response excitation systems (including special exciters, regulators, and positive sequence networks). The effect of special design characteristics on system stability is treated.

62. "Super Excitation." D. M. Jones, *General Electric Review*, Vol. 30, Dec. 1927, pp. 580-582.

Discussion of a special form of high speed excitation. Applied to synchronous condensers it offers considerable increase to the stability limits of a power system. Comparison of super excitation, quick response excitation, and standard excitation.

63. "Super Excitation to Protect Conowingo System." *Power*, Vol. 67, Jan. 31, 1928, p. 272.

Brief description of special excitation for terminal condenser equipment on Conowingo system.

64. "Electrical Characteristics of Transmission Circuits." William Nesbit, Westinghouse Technical Night School Press.

Very complete reference book of transmission line calculations.

VOLTAGE STANDARDIZATION

65 (a). *Voltage Standardization, From a Consulting Engineer's Point of View.* R. E. Argersinger, TRANS. A. I. E. E., Vol. 46, 1927, p. 172, (Discussion).

65 (b). *Voltage Standardization, Its Relation to the Interconnecting Power Companies of the Southeast.* H. J. Scholz, W. W. Eberhardt, and S. M. Jones, TRANS. A. I. E. E., Vol. 46, 1927, p. 187, (Discussion).

65 (c). *Standardization of Voltage Ratings for Power Systems and Equipment.* A. E. Silver and A. L. Harding, TRANS. A. I. E. E., Vol. 46, 1927, p. 175, (Discussion).

65 (d). *Voltage Standardization of A. C. Systems.* F. C. Hanker and H. R. Summerhayes, TRANS. A. I. E. E., Vol. 46, 1927, p. 161, (Discussion).

The four papers discuss voltage standardization from the viewpoint of the consulting engineer, operating engineer and manufacturer.

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# Discussion

## PAPERS ON INTERCONNECTION AND ITS EFFECT ON POWER DEVELOPMENT

EGLIN, MITCHELL, DOWNING, GEAR

**C. L. Edgar:** Inasmuch as none of the papers in this symposium touches upon New England, it may, perhaps, be appropriate for me to tell you, in a few words, what the situation is in that part of the United States.

As you will see by the map in the accompanying Fig. 1, interconnection has been carried on in almost every center in the New England States. Owing to the restrictive export laws of the State of Maine, there is no transmission line crossing the Maine-New Hampshire border, but in the other five states there is scarcely a center of distribution which is not connected with some other center, either in the same or in one of the neighboring states.

I have looked over the latest map of the interconnection systems of the United States and have compared the density of these lines in New England with the remainder of the country. This comparison shows that, with the exception of Maine, the density is as great in the other five New England states as in the leading eastern states of New York, New Jersey, and Pennsylvania; perhaps not quite as dense as those centering around Chicago, but considerably more so than in any other part of the United States. Distances, however, are short and interconnection has not attracted as much attention with us because of this fact as in some of the more scattered centers of the rest of the country. So much for the situation in New England.

I am very much impressed with the papers in this symposium. They cover reduction in plant capacity, reserve capacity, sizes of generating units, reduction in investments, differences in peak hours, and in fact all the various problems which have to do with deciding whether the time is ripe for interconnections and if so, how they should be brought about.

They give considerable attention to what, in my mind, is one of the most important factors in connection with this whole subject, and that is the necessity of maintaining an adequate control over the operation of an interconnected group in order to secure maximum results. This is, perhaps, merely another way of saying that the load-dispatching system of an interconnected group is the heart of the whole question, and it must be solved not only from the engineering but from the executive standpoint on very broad lines.

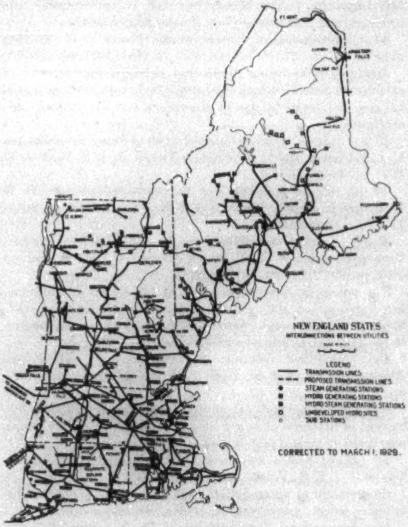

NEW ENGLAND STATES
INTERCONNECTIONS BETWEEN UTILITIES
LEGEND
TRANSMISSION LINES
PROPOSED TRANSMISSION LINES
STEAM GENERATING STATIONS
HYDRO GENERATING STATIONS
HYDRO STEAM GENERATING STATIONS
UNDEVELOPED HYDRO SITES
SUB STATIONS
CORRECTED TO MARCH 1, 1929.

FIG. 1

They also discuss some of the difficulties arising from improper, inadequate, or unnecessary interconnection. It does not seem to me that they stress sufficiently the inadequacy of some existing interconnecting lines. Some engineers seem to assume that if two systems are connected together, even by what is commonly called a shoestring, they have accomplished their purpose. They are, in fact, going in the right direction, but have only made a poor beginning. The writers especially emphasize the interruptions caused by lightning troubles and improper insulators, and other questions of this same general character.

One, at least, of the papers also refers to the effect which the introduction of high-tension underground cables is likely to have upon the entire interconnection problem. In fact, the writers seem to have covered all phases of the question.

A year or two ago it was my privilege to present the problem of interconnection, especially in New England, before a body not at all connected with engineering or with public utility work. I tried to explain what interconnection really meant in terms or in a language with which they were familiar. It may not be out of place, although I am talking to engineers, to make the same sort of comparisons that I did at that time.

I started out with the statement that interconnection was no new problem. As far back as 1892, the three generating stations of the Boston Edison Company were connected together so that the one which was located on the water front, and therefore had condensing engines, could relieve the other two, which were located on interior streets and were running non-condensing. This was as much true interconnection as that which is shown in Fig. 2 and which has recently been given considerable space in the public press. Electricity was started in Boston and carried through to Chicago on the one hand and down into Florida on the other. I do not mean to imply by this statement that any current was actually carried, but this was the general interpretation that was put on it by the newspaper articles. What actually happened, of course, was that the three centers were connected together electrically, that the systems were all in phase, and that current actually flowed between all these points. The same thing happened when Boston and Chicago were connected together a year or two ago.

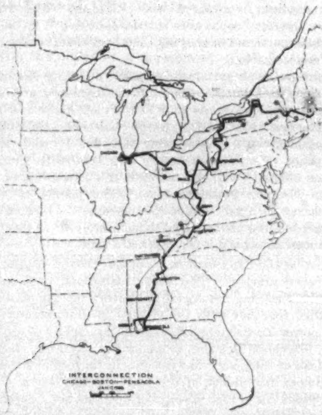


FIG. 2

In trying to bring out the fact that interconnection was no new thing and that it was developing along absolutely normal lines, I used two illustrations of similar developments in our industrial or rather in our transportation life.

The first of these was the federal or state construction of highways, and the second was the development of the privately owned steam railroads of the United States. Using the Lincoln Highway as an illustration of highway development, let us study the methods by which it is being brought about.

Of course the title "Lincoln Highway" has kept this particular development in the public eye. If it had been designed merely as a method of connecting up existing systems of roads so that a main thoroughfare thus would be created between New York and San Francisco, it would, as a matter of fact, have attracted very little attention. The name, however, caught the public eye, and today, or if not today at some time in the near future, one can travel from coast to coast seeing the Lincoln Highway sign throughout the entire distance.

As a matter of fact, the road from New York to Philadelphia was in existence long before the name "Lincoln Highway" was thought of. Some changes have been made, corners have been cut off, roads have been straightened, but these all would have come about in due course in any event. What is true between New York and Philadelphia is true between many other cities on the line of the Lincoln Highway. There were, of course, certain districts that were covered with automobile roads which were separated by many miles from other districts covered in the same way. These districts, where they came close to one another, were connected by a first-class road, and the Lincoln Highway, therefore, came into existence between these centers. Whereas the open gaps were small in the East, they became larger as one traveled westward, and even now some gaps are not yet filled. The Lincoln Highway, when completed, will be nothing more than an interconnection system, enabling the citizens of one city to travel to neighboring cities, and citizens of those, in turn, to travel to other cities, and so on ad infinitum. The problems which have arisen in the development of this transportation system have their exact parallel in the development of our interconnecting systems.

Another illustration: The steam roads of our country, a half century ago, were in a situation similar to that of the automobile roads of fifteen years ago, or to our power line situation as it is today. The interconnection in steam roads has been practically completed, whereas the automobile interconnections are in process, and the power-line interconnections are progressing to almost the same extent.

Referring to the railroad analogy, the Pullman Company, by an arrangement with all the roads, has enabled passengers to go from New York to Chicago, or from Chicago to San Francisco, without change. It is merely an interconnecting system, providing an interchange of passengers from one community to another with ease.

If the Pullman Company did not exist and there were no company doing their sort of business, the effect upon the railroad companies' investments would be tremendous. If the Pennsylvania Railroad, for example, had to own all the parlor, sleeping, and dining cars required to take care of the peak of its business, and every railroad in the country had to do the same thing, the number of cars of this character necessary to be owned by all the railroads would be far in excess of the number now owned by the Pullman Company. If, in order to preclude some of this tremendous investment, an arrangement were made between these companies for borrowing one another's equipment, it would cut down some of this investment, but it would not nearly reach that which now exists as a result of the Pullman Company's existence.

For example, the New Haven Railroad, on the day of the Harvard-Yale race at New London, or of the football game, either at Cambridge or New Haven, has to call upon the Pullman Company for a number of parlor cars far in excess of what the New Haven Company would own if it had to supply its own equipment. Possibly it might borrow a few from the Pennsylvania on the one hand and from the Boston & Maine or the Boston & Albany on the other, but if these cars did not happen to be idle or located at the proper terminal, they could not be depended on with any degree of certainty. These things are well known to all travelers.

Here again the parallel between railroad interconnection and power-line interconnection is very clear. The Pullman Company in the railroad world is equivalent to a reserve in the power industry which can be shifted from one section to another as the needs for it arise. For the same reason that interconnection among the railroads has enabled the products of one district to be easily transported to another and thus to be of advantage to both districts, the construction of these interconnecting power lines is enabling water powers, on the one hand, and steam powers on the other, to work hand-in-hand. Until very recently steam powers could not avail themselves of the advantage of cheap water power for their base load, neither could water powers gain the advantage of steam connections for reliability. This development, therefore, has marked a new era in combining the advantages of steam and water power into one enterprise.

The conclusion that I want to draw from all this is that the highways for automobile traffic and the power lines of the country are all working in the direction of saturation, a saturation which was achieved by the steam railroads many years ago. The electric power companies and electric interconnections are going through exactly the same program that the steam roads went through when they were in process of building.

Interconnection is just as inevitable in electric circuits as it is in the world of transportation. The various steps by which this will be brought about are just as unknown as they were in the railroad world a quarter or a half century ago. All that we can say is that they are bound to come if experience in other lines is any criterion.

If a word of warning is needed, it would be well to bear in mind that there are many cases in existence where railroads have built unwisely and unnecessarily. Possibly when the construction was undertaken, the needs were apparent, but in the light of later years the need has disappeared. This is also true, possibly to a lesser degree, in highway construction.

We must realize that interconnection in itself is not a panacea for all ills. It must be used intelligently, having in mind not only the light of today, but the probabilities of tomorrow. It is the preparation and presentation of papers like these which will do more than any other one thing to prevent the mistakes of the future.

**A. C. Marshall:** In Mr. Eglin's paper it is pointed out that the advantages of interconnection arise from diversity of one kind or another, which leads to a consideration of the many kinds of diversity which exist, some of which are often overlooked.

There may be diversity as to the shape of the daily load curve, or diversity as to the annual load curve. There may be diversity not only as to the annual load curve but also as to the annual variations in available capacity, such as changes in water-power capacity in wet and dry seasons. There may be diversity due to latitude and longitude, and there should be, of course, the artificially made diversity as to the program of construction in the two systems. There may be diversity in the character of population—in their habits of living, working, and play. There may be diversity in the character of industry which would affect the amount of electricity used and the time in which it is used.

It would be hard to justify the expense of interconnecting two systems that were identical in all these respects. As a matter of fact, no two such systems could exist, because if the systems were large enough to qualify under this discussion there would necessarily be a difference in geographical location, involving at least a small difference in time.

It is not necessary to explain here how these various brands of diversity get in their work. Some of them are inherent in the nature of things, but some of them are more or less under control, A change in the prevailing working hours of industry is to a certain extent in the latter class. It is doubtful if the periodic spring and fall changes of the clock to provide more afternoon daylight have had any appreciable effect on the daily load curves, especially considering the fact that such changes are made in the summer season when the daily peak is not in evidence.

There are, however, districts where permanent changes in the clock have been made which being effective the year round have changed the load characteristics of some public utilities.

When the railroads first adopted standard time in the early eighties the country was divided into zones, the time to be uniform over each zone and the time of each zone to differ from that of the next by one hour. The zones were laid out so that the time for each zone was the correct sun time for the meridian running through approximately the center of such zone. This was a natural arrangement, but in view of our present appreciation of afternoon daylight we would probably do it differently now. As the arrangement was made, the people living along the eastern edge of each zone were deprived of about one-half hour of daylight in the late afternoon. This was not noticed particularly for some time although the movement for daylight saving started some years before the World War. The War gave it a big boost and it has since become very popular.

If the standard time for each zone had been fixed as the sun time of the meridian running through the eastern edge of each zone, no one would have been deprived of any afternoon daylight although some would have had more than others. To illustrate, if the Central Time zone had been made as it is, but if the time had been fixed as that of the 82nd meridian instead of the 90th, and the time of the eastern time zone had been fixed as that of the 68th meridian instead of the 75th, we think now everyone would have been happier. All of which leads up to the situation in Detroit and eastern Michigan.

According to the original standard time layout Detroit was put on Central time, that is, 90th meridian time, being on the extreme eastern edge of that zone. Windsor, across the river in Canada, was running on Eastern, or 75th meridian time. This arrangement deprived Detroit of one-half hour of afternoon daylight, compared with true sun time, but of a full hour of afternoon daylight, compared with Windsor. This was the reason why Detroit people were so reluctant to change and why many of them persisted in keeping their own clock set for the old sun time for a long while.

After some years an agitation began for adopting eastern time for legal time in Detroit. After much discussion and several votes the change was made and Detroit officially and legally adopted Eastern time, although the railroads still published their timetables with Central-time figures. It took another long campaign of education before the Interstate Commerce Commission officially told the railroads to operate in and out of Detroit on Eastern Standard time. The people of Detroit liked the change so much that it soon became the fashion in the State to make similar changes and today almost all of the eastern half of the state runs on Eastern Standard time.

The effect on the daily load curve of the Detroit Edison Company has been marked. The winter afternoon peak has disappeared. All the big industries in Detroit operate on an 8-hr. day and this, together with the change in time, results in the afternoon power load's going off, even in the middle of winter,—before any afternoon lighting, to amount to anything, comes on. The peak load of the year usually occurs in the forenoon and may occur in almost any month of the year. It has occurred in the past few years in June, December, November, September, October, and February. The change may have resulted in the loss of some kw-hr. of lighting in the afternoons, but a small gain in kilowatt-hours no doubt occurs in the morning due to the later sunrise, by the clock. On the whole the saving in capital charges due to the absence of a sharp afternoon peak more than offsets the loss of a few kilowatt-hours.

There has just been completed an interconnection line between the Detroit Edison Company system and that of the Consumers' Power Company. The average day load of the Detroit Edison Company is now about 450,000 kw., while that of the Consumers' Power Company is somewhat less than this. This is an interconnection where a great many of the varieties of diversity are absent. The general load characteristics of the two systems are about the same. Both companies operate in a state formerly agricultural, but rapidly becoming industrial. The daily load curves of the two companies look very much alike. However, the expense of the interconnection was justified in the opinion of both companies by the ability to coordinate the construction programs of the two companies and by the diversity brought in by the large amount of water-power capacity in the Consumers Power Company's field.

This line consists of a single circuit of No. 0000 copper wire on steel towers, spaced about 800 ft. apart. The line operates at 132,000 volts. The line connects with the Consumers' Power Company's 140,000 volt system and with the Detroit Edison Company's lines at Superior substation near Ypsilanti. The line was first put into experimental operation two weeks ago and has already proved of service to both companies. The line is connected to both systems through transformers with oil circuit breakers on each side of each transformer. Complete metering equipment is installed at each end of the line.

Some study has been made of the possible advantage of extending this line west and southwest to reach the northern Indiana district. While it is too early to make many statements regarding this project, it is very evident by a little study that the difference in the daily load curves due to the difference of one hour in time would make such a connection desirable.

On the whole it seems that the engineering of interconnections has been worked out farther and better than the commercial or contract features. A great variety of contracts are in existence but there seems to be room for improvement. Where the two systems to be connected are not owned by the same corporation there is a need for a simple but equitable form of agreement that does not require a Philadelphia lawyer and a Schenectady engineer to interpret.

**James Lyman:** Mr. Gear has covered more particularly interconnection in the Chicago District. In the country districts of the Middle West the era of interconnection was inaugurated in 1912, with the adoption of an aggressive policy to serve every town in Illinois over a 33-kv. interconnected system from power stations located at economic points. From this beginning the movement has spread with increasing momentum until it has nearly covered most of the states of this region. As the system grew, 33 kv. became inadequate as a primary transmission voltage, and other systems of transmission lines at 66 kv. and 132 kv. have been superimposed on the 33-kv. system.

The accompanying map, Fig. 3, shows the 33-kv. interconnected system covering ten states having 17.3 per cent of the land area of the United States, and 31.8 per cent of the population of the United States in 1920. Outside the urban industrial centers the principal pursuits in this region are agriculture and mining. That the policy of interconnection has had a marked influence on their growth is shown by the following figures:

During 1926 the electric-power companies in these states produced:

41 per cent of the steam electric power produced in the U. S.
14 per cent of the hydro electric power produced in the U. S.
32 per cent of the total electric power produced in the U. S.

This map shows how completely the 33-kv. system now covers the area of this region. Fig. 4 shows on the same map the system of higher-voltage lines, 66-kv. and 110- to 140-kv. connecting the principal centers of this region, and extending far beyond its boundaries. There are only one or two short breaks in these high-tension lines between Minnesota and West Virginia, and between Michigan and Missouri. Wisconsin is actually connected through to Kentucky, Virginia, and states still farther south.

Fig. 5 shows the relative central-station production of steam and hydroelectric power for each of the several states for the years 1920 to 1926. It is of interest to note that the production of power in Indiana, Illinois, and Wisconsin, practically doubled in the six-year period 1920 to 1926. It will be observed that the only states producing appreciable hydroelectric power are Minnesota, Iowa, Wisconsin, and Michigan. All the other states are practically limited to steam-electric power. While the states of Illinois and Ohio represent but 19 per cent of the area, and but 37 per cent of the 1920 population, they produce 46 per cent of all the central-station power produced in this territory.

As power generation on a large scale first grew up in the cities so also did interconnection have its beginning in the cities. As it grew it gradually covered the city areas, then reached out to the suburban areas, and finally spread beyond them to link up with the systems which, growing independently, were covering the country districts. And the final step, which we are now witnessing, is the connecting of these different power centers with high-voltage, high-capacity trunk lines. The Chicago District illustrates this evolution.

Beginning with the epoch-making Fisk Street Power Station, and followed successively by Quarry, Blue Island, Northwest, Joliet, and Calumet, and more recently, by Crawford and Waukegan power stations, this interconnection grew and spread as each successive plant, profiting by new developments, was able to produce energy cheaper than its immediate predecessor. In a measure, each plant in turn functioned as a base-load plant for the interconnected system. Because of this, each of the Chicago plants, in its turn, contained the largest steam-turbine unit available at the time.

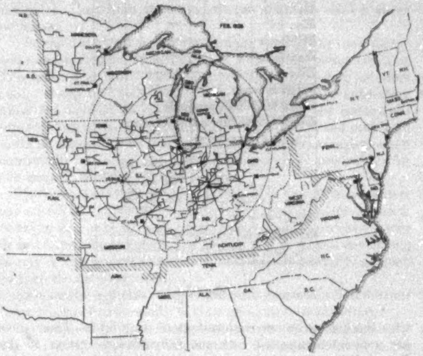


FIG. 3—33-KV. LINES IN MIDDLE WEST STATES

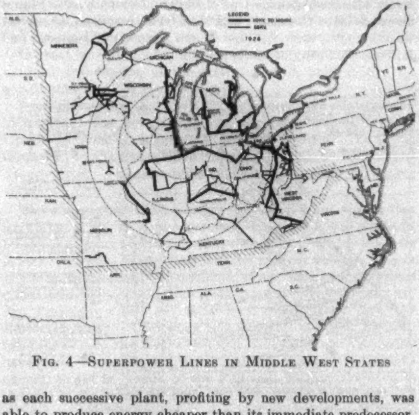


FIG. 4—SUPERPOWER LINES IN MIDDLE WEST STATES

*Interconnection of Other Systems in the Middle West.* The American Gas & Electric Company transmission system stretches from Southwestern Michigan and Northern Indiana through the states of Ohio and West Virginia to Pennsylvania, Virginia, Kentucky, and Tennessee. It connects with the transmission lines of the Chicago District on the West, the Toledo and Cleveland systems on the North, the systems of the Ohio River Edison Company and West Penn Power Company on the East, and the systems of the Carolina Power & Light Company and Tennessee Public Service Company on the South.

The 140-kv. hydroelectric lines of the Consumers Power Company in Michigan, put into operation in 1912, had at that time the highest commercial voltage in the world. These lines are now interconnected with the transmission system of the Detroit Edison Company.

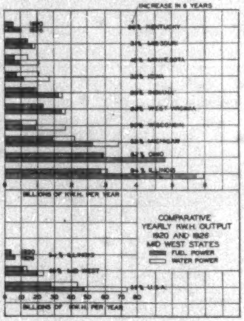
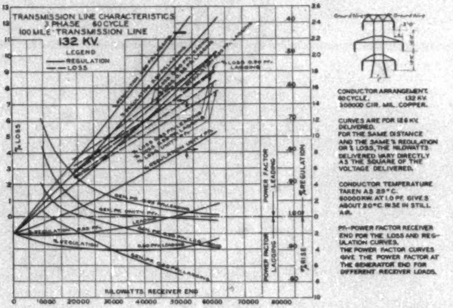


FIG. 5

The systems of the Insull companies also interconnect successively with the Columbia Gas & Electric Company, the Illinois Power & Light Company, and the North American Company on the South, and with the North American Company and Byllesby Company on the North.



CONDUCTOR ARRANGEMENT. 60 CYCLE. 132 KV. 300000 CIR. MIL. COPPER.

CURVES ARE FOR 126 KV. DELIVERED. FOR THE SAME DISTANCE AND THE SAME % REGULATION OR % LOSS, THE KILOWATTS DELIVERED VARY DIRECTLY AS THE SQUARE OF THE VOLTAGE DELIVERED.

CONDUCTOR TEMPERATURE TAKEN AS 25° C. 60000 KW. AT 1.0 PF. GIVES ABOUT 20° C. RISE IN STILL AIR.

PF.—POWER FACTOR RECEIVER END FOR THE LOSS AND REGULATION CURVES. THE POWER FACTOR CURVES GIVE THE POWER FACTOR AT THE GENERATOR END FOR DIFFERENT RECEIVER LOADS.

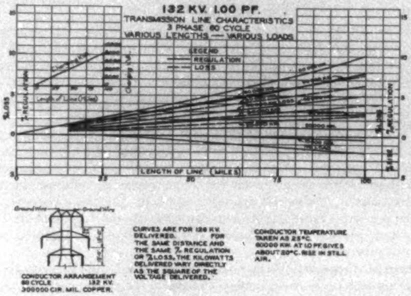
FIG. 6

*Transmission Voltage.* In the Middle West where large economical steam power stations are often located not more than 100 mi. apart, 132 kv. is a good standard voltage. Power in the order of 50,000 kw. to 60,000 kw. per circuit can be directed to or from these power stations as operating conditions dictate.

A high power factor is required and preferably obtained through the use of synchronous condensers installed at the plants of the largest customers.

Desirable flexibility of control is obtained by the use of equipments for tap changing under load, for the terminal banks of transformers.

Fig. 6 shows characteristic curves for 3-phase, 60-cycle, 100-mi. transmission line of 300,000-cir. mil copper cable, with 126-kv. delivered voltage for various power factors.



CONDUCTOR ARRANGEMENT 60 CYCLE 132 KV. 300000 CIR. MIL. COPPER.

CURVES ARE FOR 126 KV. DELIVERED. FOR THE SAME DISTANCE AND THE SAME % REGULATION OR % LOSS, THE KILOWATTS DELIVERED VARY DIRECTLY AS THE SQUARE OF THE VOLTAGE DELIVERED.

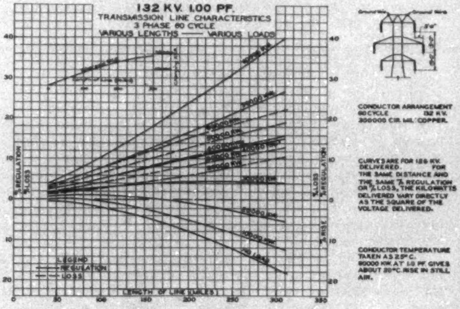
CONDUCTOR TEMPERATURE TAKEN AS 25° C. 60000 KW. AT 1.0 PF. GIVES ABOUT 20° C. RISE IN STILL AIR.

FIG. 7

Figs. 7 and 8 show characteristic curves for unity power factor and transmission lines of 100 mi. and of 300 mi. respectively.

Figs. 9 and 10 show characteristic curves similar to 7 and 8, except at 0.95 power factor lagging.

A study of these curves shows the necessity for high power factor. The increased kilowatts capacity and reduction in $C^2 R$ losses of the interconnected system very much more than pays for the capital and operating costs of the synchronous condensers. These are now being developed in large sizes for out-of-door installation, cooled either by recirculation of air or hydrogen, and with automatic control of voltage.



CONDUCTOR ARRANGEMENT 60 CYCLE 132 KV. 300000 CIR. MIL. COPPER.

CURVES ARE FOR 126 KV. DELIVERED. FOR THE SAME DISTANCE AND THE SAME % REGULATION OR % LOSS, THE KILOWATTS DELIVERED VARY DIRECTLY AS THE SQUARE OF THE VOLTAGE DELIVERED.

CONDUCTOR TEMPERATURE TAKEN AS 25° C. 60000 KW. AT 1.0 PF. GIVES ABOUT 20° C. RISE IN STILL AIR.

FIG. 8

Fig. 11 shows a steel tower typical of the design used in the Chicago district.

Experience with 150 mi. of such 132-kv. heavy power circuits in the Chicago District indicates that when the circuits are equipped with ground wires and shielding rings the number of interruptions is practically negligible. Where shielding rings are used to protect the insulator strings, in case a flashover does occur, the line can immediately go back into service without inspection or repairs. Transformers and other high-tension apparatus are now made to give equal reliability when properly protected by the most approved lightning arresters.

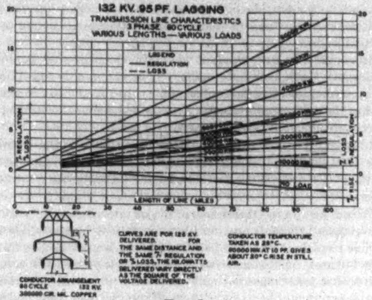


Fig. 9

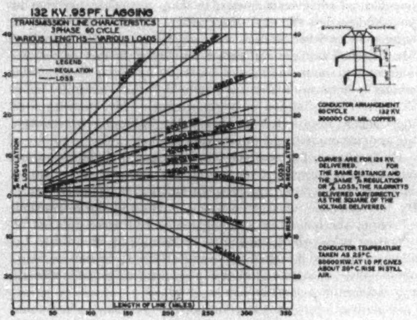
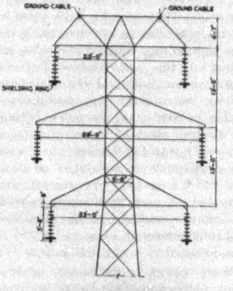


Fig. 10



TYPICAL 132 KV. TOWER
USED IN CHICAGO DISTRICT

Fig. 11

*Advantages of Interconnection.* Interconnection makes available throughout a wide area the power from a number of large generating stations. It permits their most favorable location with reference to fuel and water supply. By diversity of the system load a much higher load factor is obtained, thereby reducing in direct proportion the required active generating-station capacity. Further, the reserve generating capacity need only be a fraction of that required were the stations operated independently. The combined saving in generating capacity due to diversity in load and to reduced reserve is in many cases very great.

The entire interconnected territory is served from several sources of reliable power supply so that in case of failure of any generating unit or transmission-line section, the possibility of interruption of power supply is remote. Instances of this character taken from actual experience might be cited if space permitted.

The rapidly increasing power demand throughout the country necessitates frequent installation of new steam power stations. The latest and most economical stations can operate as base-load stations for the system. The most economical generating units can operate as base-load units, and the less economical units or stations can be operated as semi-peak-load and peak-load units or stations; thus the interconnected power companies can continually maintain the highest economies of production for the large bulk of their power supply.

The operators in power stations located at the different centers can advise each other over their carrier systems of communication, of rising storms in advance of their arrival, and thus their power demands may be anticipated. Also, in case of trouble developing in one of the several stations, the others can promptly prepare to take the necessary load.

Frequently systems under different ownership interchange large blocks of power daily to their great mutual advantage.

Interconnection has made economically possible practically the universal supply of electric power, the greatest factor in the continued prosperity of our country.

**Farley Osgood:** That interconnection is useful seems no longer to be a question. I shall try to generalize on the whole subject and summarize what I have learned from these papers and observed in my work.

In these four papers I think unquestionably we have the best national presentation of the interconnection problem and its possibilities that has ever been given.

I am glad to see that the fantastic names formerly given to high-voltage line interconnections are going out of fashion. I noticed on one chart presented the word "super." In all the discussion on these papers, I think it is the only time that word has appeared. I think it will soon be wrapped up and will appear no more.

There is no such thing as super power, or giant power; that isn't what it is. It is just the everyday work of the electrical fellow connecting together his physical links. That is all there is to it. As Mr. Edgar described the railroad and the Lincoln Highway development, it occurred to me that some day there might be a physical-electrical connection between Boston and San Francisco which we might very appropriately term the Edison Highway. There may be a complete electrical highway from the East to the West Coast and just as the passenger today can get on a train in Boston and go to California (and if he is lucky enough to get in certain of the Pullmans he may not have to change) so too, when we have the Edison Highway a kilowatt can get on the highway at Boston and reach California by being shoved along by the various systems hooked into the interconnection.

That is the picture we should give to the public. We should destroy as fast as possible and whenever we get an opportunity, any thought that California will furnish current to New England or vice versa. It is absurd and it is the duty of the electrical engineers to explain to people why it is impracticable.

We should not make any extravagant statements so that newspaper reporters, politicians, and anybody who may not understand our language will misinterpret it to our detriment before the public.

A word about the financing of these inter-system lines: It isn't any kindergarten problem, this laying out and completing and financing a major interconnection. Engineers must understand that tremendous amounts of money are required and it is their duty to prove to their executives responsible for the financing of their undertakings that a large investment must be made in advance of actual income, because these things take more than two years to do and sometimes take three, five, or ten years before full realization on the capital invested. Financiers who back us in our work should not be afraid to do so, but we should tell them what to expect in the way of return at first, and year by year thereafter, because they depend on us and our statements should be clear and conservative.

The usual possible economies of interconnection have been dwelt on so much that I will not even mention them. We all know what they are.

I should like to emphasize the fact that the strongest construction possible under the economic condition of the work undertaken is an essential, not only because the service is dependent upon these major interconnections but also the growth of the respective systems usually is faster than we expect and an early avoidance of duplication of construction is there if we build large and strong in the first place.

Continuity of service of course also depends upon the sturdiness of the construction, assuming that it is of the proper type for the service.

I notice that there are only two or three large pieces of work going on in the country at the present time of the highest service voltage, namely 220,000 volts. The California fellows developed this voltage as soon as the originating engineers felt it safe to have them do so. This ring here, near New York, connecting electrically Philadelphia, Newark, and the coal fields of Eastern Pennsylvania is also a 220-kv. system.

In the discussions of the Chicago situation I note that 132 kv. has been adopted as the maximum voltage apparently desirable for that district. Far be it from me to criticize because those gentlemen have proved they know where they are heading, but just as a general word of caution, I should like to say: when building, make your voltage as high as the traffic will bear at the time, because you will save yourself a lot of trouble in the future. Even if you do not operate at the highest possible voltage available at the time, have that in mind when your right-of-way is purchased, when the spacing of your conductors and towers, etc., is laid out so that if fortune or big business overtakes you sooner than you dared hope, you can save your executives putting up additional money too soon.

The synchronous condenser is a joy to the operating man in helping him pull up his voltage. It was interesting to hear the last speaker say the best place for the synchronous condenser was on the big customer's property and I might also add, to be bought at his expense.

The customer can be given a favor in the way of rates, if he helps pull up the power voltage of the whole system. It works both ways.

The matter of selective relays for the eliminating of lines and trouble, is a question about which we have had so much discussion, I am afraid to say anything about it, except where you do not have to be tied in solid for a proper reason, if you can eliminate any circuit that is in trouble of course you are going to save slams on your whole system and you are going to add to the safety and protection of your generators and your transformers. I think where the loose-link system can be used, it is healthier for the apparatus.

The Chicago paper was the only one which mentioned the use of high-voltage cable. I believe that is one of the things that the transmission engineers need most for their service at this time.

When we were designing the 132,000-volt domestic ring for New Jersey service, if we could have obtained cable at the time, it would have saved us a great deal of trouble and because we could not get high-voltage cable to go through a congested area we had to go outside into the country with open lines which cost much more than the cable would have cost if it had been available.

In congested areas, think of what Mr. Gear has told us about Chicago. Cable is indispensable. If he can double the voltage of his interconnecting cables from 66 kv. to 132 and to 220 where he has these tremendous loads, think of the money he is going to save and the comfort he will have.

In these installations, it is desirable to have every possible recording instrument and device of every nature to make record of the actual performance of the line and everything connected with it in regular service and particularly at times of failure.

We are just on the threshhold of major interconnection work in America and the only way to learn about it is by absolutely infallible records. We have had to go by guesswork largely up to date but now devices are coming into service which will record for us what takes place normally and under abnormal conditions. Let no argument of cost have them eliminated from your budget. If you do not have anything else, be sure and get all the best possible recording instruments; in fact, you might put that in your budget first and say "If we cannot record what is going to happen to us when we get through, we do not want to build." Mr. Mitchell brought out rather pointedly the fact that interconnected systems could get much better operating results if the several systems are under one ownership, which naturally tends to a closer coordination of personal effort. Mr. Downing cites the excellent results that are obtained in California even though the systems are not under one ownership.

By frankness, fairness, the elimination of individual system selfishness, it is perfectly possible to get, if not the very highest efficiency of operation, at least an entirely satisfactory result. By the formation of a committee composed of the responsible officers of the individual systems, which will make up a set of operating rules, which rules must be thoroughly understood by all operators, and if carried out to the letter by a master operator, unanimously selected and in absolute operating control, efficient and satisfactory operation can be obtained.

In closing, I just want to point out the two things which seem to be the weak links in our chain at the moment and urge the engineers responsible for these two weak links to get all of this discussion in their minds that they may need to help them develop their art so that we may have these links up to the strength of every other link in our electrical systems. The two weak links are high-voltage underground cable, and oil switches.

**E. C. Stone:** At this time, because of the recent rapid extension of transmission lines and the multiplication of interconnecting links, which make the transmission-line map look something like a railroad map, the public is prone to conclude that there is no limit short of the continental confines of the United States to the transfer of energy; and when the minds of legislators are considering the necessity for federal regulation of power systems which are rapidly over-reaching state boundaries, it is important that engineers particularly, in their speeches and writings, give proper emphasis to the limitations as well as advantages of interconnection so as to be sure that the public does not get a distorted view of the situation.

There is already before us the history of three great public utility services which grew from local beginnings until they covered the entire country and the transfers of the commodities handled by them became nationwide in extent—namely, the railroads, the telephone, and the telegraph. There are inherent reasons, however, why this movement in the electric power industry will not be carried to the same limits.

The articles of commerce carried by the railroads differ widely in character, and the wants and likes of the consumers of the country are sufficiently strong and varied so that they are willing to pay the cost of transferring these articles to points all over the country. The fruits and vegetables of California are consumed throughout the states. The shoes made in Massachusetts are sold in St. Louis, and I have no doubt that St. Louis made shoes are sold in Massachusetts. The messages transmitted by the communication companies are all different regardless of the relative locations of the source or destination; hence the nation-wide movement of such messages. In the power industry, however, all kilowatt-hours are alike so that the consumer will always take advantage of the obvious economy of obtaining his kilowatt-hours from the nearest source of power.

Interstate transmission of electric power is the result of the natural physical relation between the markets for power and the nearest suitable sites for the location of economical power plants. Thus the transmission of power is essentially local in character, and very few instances can be found where any given block of power is transmitted across more than one state boundary. An analysis of the output of eighteen generating plants from which is produced approximately 45 per cent of all of the power transmitted over state lines, shows that the average distance of transmission from plant to point of utilization is less than 75 mi. Probably the average mileage of all interstate transmission would not exceed this figure. Although many plants located in many different states are being electrically connected, the effect of such interconnection is merely to distribute the combined load among the various plants more nearly in proportion to their capacity. It does not to any measurable extent increase the radius of transmission of power from any of the individual plants in the group.

Hence the power situation is again radically different from that in respect to freight handled by the railroads, which in some cases is shipped across a great many state lines. In this connection, Secretary Hoover spoke as follows at the 37th Annual Convention of the National Association of Railroad and Utility Commissioners at Washington, D. C., October 14, 1925:

"The argument is sometimes used that the power situation is parallel with the railroads, where federal regulation has been found necessary. It differs in several profound respects. Power has no such interstate implication as transportation. The grower of oranges shipping from California is affected by the freight rates of every different railway all the way to the Canadian border and the Atlantic seaboard. The same farmer as a buyer of power is interested in only one power company—the one in his immediate neighborhood. What the rates may be of 200 other power companies between him and the borders of the continent do not affect his rates in the remotest degree. Therefore one state is not vitally interested in the rates of another state as in the case of the railways."

As a result of these inherent limitations, only 6,172,000,000 kw-hr., equal to approximately 9 per cent of the total of 68,145,000,000 kw-hr. generated during 1926 by the electric light and power companies in the United States, were transmitted across state lines. This is in striking contrast to conditions with the railroads, of whose business probably 70 per cent to 80 per cent is interstate in character.

It is reasonable to suppose that all of the power required for use within the individual states could be generated within their own boundaries, so that interstate transmission would be unnecessary, but this would result in less use of water power, in higher cost of fuel, in longer transmission distances and, in many instances, in greater first cost of plant on account of utilization of less favorable locations, all of which conditions would increase the cost of power. The margin of profit to be realized by interconnection is narrow, however, and if, as a result of misconception, burdensome restrictions were placed on such interconnection, it is reasonable to assume that public-utility companies, finding themselves hampered by requirements and regulations so burdensome as to offset any advantages to be had, will curtail their interconnections and thereby the consuming public will lose those limited advantages which are now being utilized or being sought.

Therefore, it is to be sincerely hoped that no artificial barriers will be set up which might result in restricting this sort of transmission in such a way as to increase the total cost of the production and delivery of power.

The economies resulting from the interconnection of power systems as disclosed by the papers in this symposium represent all told a very large number of dollars, and are therefore well worth while. Expressed as a percentage of the cost of electric power to the average user, however, the figure will be relatively small, possibly of the order of 5 per cent. Hence the most comprehensive development of system interconnections cannot possibly bring about any radical reduction in the cost of energy to the average user of electric power.

The major engineering problems involved in the interconnection of large power systems will continue to receive careful study. These appear to be as follows:

1. Determination of the total spare generating capacity actually required to render adequate service at all times on systems of large capacity and operating many units. Due regard must be given to the periodic shut-down of machines for maintenance and the probable loss of capacity due to breakdown. Present practise of many systems provides spare capacity equal to the capacity of the largest units. It is yet to be determined whether this will be adequate when adjacent systems are interconnected, so that substantially larger numbers of units are included in one system. More attention will also be given to the most economical size of unit giving full effect to the spare capacity requirements.

2. Control of the amount of energy and reactive kv-a. passing over interconnection points in complicated networks. This will involve not only proper frequency adjustment at the generating stations but in many cases phase and voltage control at strategic points in the transmission networks.

3. System stability both under normal load conditions and on the occurrence of abnormal transient surges. In this connection it is quite probable that it will be found necessary to equip high-tension transmission lines with reactors or their equivalent at the power-house end, following the practises now generally standard on lower voltages of using line reactors which sustain the voltage of the system as a whole as well as reduce rushes of current when the individual line short circuits near the power plant.

4. Design and manufacture of circuit breakers for the voltages and interrupting capacities involved in the interconnection of large power systems.

5. Development of selective relaying schemes such that tie lines will not be interrupted when short circuits develop on one or the other of the interconnected systems. One of the chief operating advantages in interconnection lies in the fact that the loss of a single generating unit will result in a smaller percentage loss in operating capacity. This advantage is lost if tie lines are opened by system short circuits. Furthermore, the amount of power transmitted across a tie line may be greater than the receiving company can handle on its own system if separated from its interconnections so that opening of tie connections will result in interruptions to service.

**L. W. W. Morrow:** With the rapid growth of light and power systems over extensive areas it is inevitable that energy should be sent across state lines. It is rather astonishing to note, however, that the amount of energy so transmitted was only 9 per cent of the total energy generated in public-utility stations during 1926. According to the Bureau of Business Research of Harvard University the total energy transmitted across state lines in 1926 aggregated 6,171,530,837 kw-hr. while the total generation in that year amounted to 68,145,217,000 kw-hr.

TABLE I

EXPORTS AND IMPORTS ON INTERSTATE POWER BY ELECTRIC LIGHT AND POWER COMPANIES UNITED STATES—1926

| | | Interstate Power | | Net Interstate Power | |
|---|---|---|---|---|---|
| | Power Generated* (Kw-hr.) | Exported (Kw-hr.) | Imported (Kw-hr.) | Net Exported (Kw-hr.) | Net Imported (Kw-hr.) |
| *New England:* | | | | | |
| Maine | 503,105,000 | 2,803,706 | 823,946 | 1,979,760 | —— |
| New Hampshire | 259,133,000 | 15,514,336 | 47,320,485 | —— | 31,806,149 |
| Vermont | 254,508,000 | 234,544,352 | 21,207,590 | 213,336,762 | —— |
| Massachusetts | 2,097,538,000 | 226,737,240 | 420,760,736 | —— | 194,023,496 |
| Rhode Island | 405,299,000 | 79,465,342 | 154,920,753 | —— | 75,455,411 |
| Connecticut | 906,941,000 | 52,106,110 | 51,219,136 | 886,974 | —— |
| *Middle Atlantic:* | | | | | |
| New York | 9,146,059,000 | 147,214,876 | 17,112,855 | 130,102,021 | —— |
| New Jersey | 1,722,749,000 | 19,780,642 | 202,783,965 | —— | 183,003,323 |
| Pennsylvania | 7,220,386,000 | 614,801,002 | 477,281,883 | 137,519.119 | —— |
| *East North Central:* | | | | | |
| Ohio | 4,596,945,000 | 285,558,782 | 487,588,090 | —— | 202,029,308 |
| Indiana | 1,420,528,000 | 152,210,606 | 146,616,303 | 5,594,303 | —— |
| Illinois | 5,892,130,000 | 646,354,014 | 305,976,537 | 340,377,477 | —— |
| Michigan | 3,184,591,000 | 57,715,760 | 42,943,150 | 14,772,610 | —— |
| Wisconsin | 1,779,973,000 | 225,598,472 | 126,545,506 | 99,052,966 | —— |
| *West North Central:* | | | | | |
| Minnesota | 843,258,000 | 50,842,474 | 195,984,387 | —— | 145.141.913 |
| Iowa | 1,308,622,000 | 632,315,767 | 76,680,703 | 555,635,064 | —— |
| Missouri | 760,910,000 | 59,690,208 | 885,509,239 | —— | 825,819,031 |
| North Dakota | 45,393,000 | 0 | 6,194,161 | —— | 6,194,161 |
| South Dakota | 80,342,000 | 7,786,857 | 3,187,987 | 4,598,870 | —— |
| Nebraska | 358,494,000 | 19,591,133 | 1,490,491 | 18,100,642 | —— |
| Kansas | 761,429,000 | 129,960,481 | 32,631,815 | 97,328,666 | —— |
| *South Atlantic:* | | | | | |
| Delaware | 118,866,000 | 21,019,362 | 10,238,314 | 10,781,048 | —— |
| Maryland | 586,917,000 | 78,365,841 | 438,524,065 | —— | 360,158,224 |
| District of Columbia | 350,014,000 | 42,182,891 | 0 | 42,182,891 | —— |
| Virginia | 920,255,000 | 10,692,478 | 109,770,362 | —— | 99,077,884 |
| West Virginia | 1,682,968,000 | 736,930,012 | 95,349,606 | 641,580,406 | —— |
| North Carolina | 1,116,043,000 | 25,029,500 | 329,140,958 | —— | 304,111,458 |
| South Carolina | 1,023,076,000 | 318,670,000 | 67,861,902 | 250,808,098 | —— |
| Georgia | 709,705,000 | 68,094,902 | 272,418,703 | —— | 204,323,801 |
| Florida | 494,745,000 | 0 | 1,314,718 | —— | 1,314,718 |
| *East South Central:* | | | | | |
| Kentucky | 457,770,000 | 73,701,994 | 182,259,635 | —— | 108,557,641 |
| Tennessee | 893,693,000 | 21,797,033 | 11,469,426 | 10,327,607 | —— |
| Alabama | 1,138,804,000 | 283,984,216 | 8,196,946 | 275,787,270 | —— |
| Mississippi | 58,667,000 | 279,300 | 57,577,615 | —— | 57,298,315 |
| *West South Central:* | | | | | |
| Arkansas | 163,517,000 | 873,775 | 61,481,112 | —— | 60,607,337 |
| Louisiana | 514,552,000 | 82,720,682 | 15,421,073 | 67,299,609 | —— |
| Oklahoma | 429,735,000 | 11,469,200 | 85,921,944 | —— | 74,452,744 |
| Texas | 1,430,356,000 | 17,470,344 | 1,356,058 | 16,114,286 | —— |
| *Mountain:* | | | | | |
| Montana | 1,407,783,000 | 18,432,000 | 0 | 18,432,000 | —— |
| Idaho | 738,876,000 | 465,743,608 | 78,554,534 | 387,189,074 | —— |
| Wyoming | 42,084,000 | 0 | 0 | 0 | 0 |
| Colorado | 517,405,000 | 0 | 0 | 0 | 0 |
| New Mexico | 25,993,000 | 1,214,848 | 2,006,383 | —— | 791,535 |
| Arizona | 167,164,000 | 21,181 | 4,664,592 | —— | 4,643,411 |
| Utah | 347,857,000 | 0 | 421,274,000 | —— | 421,274,000 |
| Nevada | 36,553,000 | 0 | 46,019,035 | —— | 46,019,035 |
| *Pacific:* | | | | | |
| Washington | 1,716,557,000 | 73,913,249 | 97,346,669 | —— | 23,433,420 |
| Oregon | 806,296,000 | 91,167,309 | 68,562,288 | 22,605,021 | —— |
| California | 6,700,633,000 | 67,164,952 | 21,181 | 67,143,771 | —— |
| United States Total | 68,145,217,000 | 6,171,530,837 | 6,171,530,837 | 3,429,536,315 | 3,429,536,315 |

*Interpreted from United States Geological Survey figures—Bulletin 68, Bureau of Business Research, Harvard University.

Of the energy transmitted in 1926 across state lines 83.3 per cent went to markets supplied as a normal service and 16.7 per cent went to special or temporary markets. Of the total interstate energy 26.28 per cent involved no change in ownership. The number of interstate lines aggregated 463 but 81 of these carried 61.7 per cent of the total interstate power.

Three general conditions exist which may bring about interstate transmission.

The first type is a regular supply of energy to a market in a territory where generating facilities may not coincide with the location of the load. At Keokuk, Iowa, the nearest large market for hydroelectric power is St. Louis, Mo. and in Illinois; at Cahokia, Ill., a site is most suitable for a fuel-burning plant to supply energy to St. Louis. Thus the city of St. Louis receives a large proportion of its energy from plants controlled by the local utility but located in other states. Out West waterpower is in Idaho but the load is in Utah. Many examples of this type of generating-station location which supply energy to loads across state lines may be found in Ohio, Illinois, Indiana, Pennsylvania, and other states. The stations are operated to supply energy to permanent markets and are owned by the utilities distributing the energy in these markets. This type of interstate business accounts for about 75 per cent of the total energy and is not necessarily involved with major interconnections or transmission systems of large magnitude.

A second condition which brings about energy transmission across state lines is in areas where steam and hydroelectric generating facilities are interconnected for temporary or emergency energy service.

A water shortage on a hydroelectric system may cause energy to be bought from a system in another state; a hydroelectric property may be able to sell or buy energy from a utility using fuel generation; during the construction of a new station energy may be bought so as to load fully the new station when it comes into operation. Many economic combinations in a large area may exist from year to year whereby savings are made by temporary energy interchanges on lines which cross state lines. For example, in the South, Alabama may sell energy to Georgia at one season of the year and may buy energy from Georgia at another period.

The third condition which brings about the transmission of energy across state lines is found in large-capacity interconnections between utilities which operate over an extended area. It is economical on such systems to shift generating-station loads to get the best economic results. For example, the American Gas and Electric system extends from near Chicago to western Virginia. It has generating stations in several states connected by transmission lines. Energy may go to or flow from West Virginia or Ohio depending on load conditions. In the heavily loaded area of eastern Pennsylvania, New Jersey, and New York, stations may be located in several states and energy will be sent across state lines to take advantage of diversity in loads.

A study of interstate energy shows that Pennsylvania, Illinois, Iowa, West Virginia, Vermont, Alabama, South Carolina, and Idaho lead in the export of energy and that energy is imported in large amounts to Massachusetts, Pennsylvania, Ohio, Missouri, Maryland, North Carolina, Georgia, and Utah. A knowledge of generating conditions in these states shows that the exportation and importation of energy involves a few large generating stations and special conditions. For example, South Carolina waterpower goes to the load in North Carolina. Energy from the coal fields of northern Alabama and from Muscle Shoals goes to Georgia. Hydroelectric energy from Idaho goes to the load in Utah. Holtwood waterpower in Pennsylvania goes to the load in Maryland. Hydroelectric and steam power in southern West Virginia goes to Virginia and Ohio. Hydroelectric power from Vermont and New Hampshire supplies the load in western Massachusetts. Keokuk in Iowa and Cahokia in Illinois supply the energy to St. Louis in Missouri. Windsor steam station in northern West Virginia supplies energy to Ohio and Pennsylvania. Thus a few large stations or systems supply most of the energy that crosses state lines. An economic and very practical background exists for all this business.

With the modern trend toward putting loads and generating sources near together for economic reasons and because load density grows rapidly it is evident that long-distance transmission projects involving interstate energy traffic will not become of great importance and that special conditions in the future, as in the past, will control interstate energy traffic. There is no reason to expect interstate energy to grow at a rapid rate or at a rate corresponding to that at which the light and power industry will grow.

**W. S. Lee:** It would be impossible for me or anyone to enter into any detailed discussion of the problems of interconnection or parallel operation of power systems.

This matter has to be developed in connection with the particular system or section of the country. There are certain waterpower developments, limited in number, and the time will soon come when they will all be developed. There are growing up around these plants and in the territory which they are near, certain demands for power that should be furnished from the nearest point of generation.

Efficiency, economy, and reliability of service has caused various hydroelectric and steam stations to be connected. This interconnection of local hydroelectric and steam stations produces the big central-station system. The central-station system assumes the duty of service to all contiguous territory.

Now the phase in which the engineer today is going to function is to build the water plants at such locations determined by the physical conditions, such as head storage, etc., then intersperse among these plants at the proper place on the load centers, steam stations.

Two important factors in connection with the design of steam stations are load factor and size of plant. The larger the central system the more opportunity the engineer has to build these plants efficiently and economically. The larger the system developed the better opportunity he has of locating these stations so as to shorten the transmission lines and thereby lessen the cost of power to the consumer.

I am delighted to see these papers for if there is any abused subject it is super-power and giant-power. Every engineer is aked the question, "How far can you carry electric power?" You all know it is not economical to carry it very far. The result is, there is an impression that power can be taken in great amounts from one section and dumped into another economically. You can't do it.

Mr. Mitchell's paper gives a very fine description of the Southern Systems. The Duke System tied in with the Eastern Carolina in 1908 and this connection has been found very useful from time to time ever since. About 1911 the Duke System tied in with the Georgia System. Both of these connections have been used for exchanging power and shifting power from one system to the other, but to carry large blocks of power great distances has not been done. I am glad to see that the whole trend of this discussion has not been for the purpose of carrying power in large blocks to great distances but to lay out hydroelectric and steam stations in a connecting system for the purpose of shortening transmission distance.

**C. F. Hirshfeld:** I have been asked to present, by way of discussion, material on what is commonly designated as loose linkage.

In presenting matters of this sort one is greatly handicapped by the fact that our language grows as required by the development of the art so that the art is always ahead of the language. As a result, it frequently takes a long time for a given expression to acquire a very definite meaning and in the interim there is much danger of misunderstanding. I shall therefore attempt to indicate the meaning of each questionable term that I use.

The term loose linkage, as contrasted with tight linkage, is first used to indicate a system of connections adapted to fall apart comparatively easily in case of trouble, in contrast to one in which connections are intended to be maintained intact as long as it is physically possible to do so.

We all recognize the fact that with present equipment and present methods we must expect troubles of various sorts which result in temporary reduction of voltage and increased flow of current. In a simple, generalized way, these troubles may be divided into two classes, those which correct themselves quickly by being cleared in some way, and those which do not, which "hang on" as we say. These may, for present purposes, be designated as controllable and uncontrollable respectively. With respect to the first class, there is a decided advantage in having connections remain intact in order to give the most immediate return to conditions of normal service after the trouble has been cleared. With respect to the second class, there is a decided advantage in having certain links break easily so as to confine uncontrollable trouble to the smallest practicable area, thereby producing a minimum of disturbance to the system as a whole and no long time effect upon service to the remainder of the territory.

Thus far probably all will agree. It is when we go beyond this rough generalization that we enter the argumentative zone. As I see it, the direction in which the next step leads depends partly upon one's experience, partly upon one's idea of character of service, partly upon one's estimate of the sorts of trouble to be experienced, partly upon one's estimate of the frequency of the different sorts, and partly upon the type of system with which one is dealing.

We may well consider extreme examples to bring out the great differences that are possible. Take as one case a system completely underground and consisting of a perfect network to which energy is furnished from a number of multiplied sources. Take as the other case a system which is entirely overhead, arranged practically radially throughout and in a territory in which lightning storms are prevalent. One would hardly expect the operators of such widely divergent systems to adopt similar ideals of service or similar methods for handling troubles of the type here referred to.

We must then admit that in all probability both loose-linkage and tight-linkage systems have their proper fields of use. At least, I do not desire to be understood, in what follows, as advocating one or the other under all different conditions.

An ideally developed loosely linked system may be assumed to consist of a collection of areas so arranged and so served that each can readily become self-contained and self-sustaining in case of uncontrollable trouble in one or more other areas. For want of a better term I shall call each of these a power area.

In the ideal loosely linked system, each power area normally operates in synchronism with all the others during all periods of normal operation. However, a power area subject for the time being to uncontrollable trouble cuts loose completely and automatically from all other power areas. It then shifts for itself as best it can until those in charge have had an opportunity to clear the situation by any means that may be available, after which it may once more be synchronized with the remainder of the system when, as, and if that becomes desirable.

These requirements necessitate certain characteristics which may be listed as follows:

(a) Each power area must be capable of becoming self-sufficient practically instantaneously.

(b) All power areas must be so tied together under normal conditions that the necessary synchronizing currents may flow.

(c) All power areas must be so tied together that any one developing uncontrollable trouble will automatically cut itself loose from the others before service in them is seriously menaced.

Requirement (a) indicates immediately that each power area must have sufficient running reserve, or the equivalent, to care for the total existing load within its boundaries if it happens to be isolated because of trouble in one or more other power areas. This does not mean that each power area must at all times be supplying all the power consumed within that area. The distinction should be carefully noted. Power may flow across power-area boundaries as may be required to affect most efficient or most convenient plant operation. The only requirement is that each area thus supplied from outside its boundaries shall have sufficient running reserve to care for itself if this supply is suddenly interrupted. The requirement is easily met through the reserve capacity of turbo generators above their best points when the sizes of units in the system are properly coordinated and when the boundaries of power areas are properly chosen.

Self sufficiency with respect to power supply may be obtained by the use of one or more generating stations per power area or by the use of one or more major switching stations supplied from several sources over different routes, both sources and routes being so chosen as to minimize the danger of complete loss of supply. In this connection, it should be noted that the boundaries of power areas need not be fixed and, in general, will not be fixed. This statement applies to different hours within one day as well as to different days, different weeks, months, seasons, and years. It is only necessary that a boundary is known to exist at a certain place at a certain time and that the ties crossing that boundary at that time are properly relayed to prevent them from transmitting a major disturbance.

It will probably be granted that at least under the majority of conditions existing in this country, the loosely linked system offers the greatest security against a major catastrophe to the system as a whole. Undoubtedly, operation on this basis requires a very high order of engineering in planning and constructing and extending the system. Undoubtedly also it calls for very intelligent cooperation between system operator and plant operator if the maximum of results of all sorts is to be obtained. It is probable also that the load dispatcher or other individual who handles system operation must give more thought to the details of his job than he must with a tightly linked system, if the best results of which each system is possible are to be obtained. There is admittedly room for argument as to whether the results obtained from loose linkage justify these costs in human effort. Some executives have demonstrated that they believe the results obtainable do justify such costs.

We may say that there is really a radically different point of view back of the two systems of linkage. In the one, the necessary occurrence of uncontrollable difficulties is recognized and the maximum of security to service is provided by arranging power areas capable of instantaneously becoming self-sufficient. In the other it is assumed that such major uncontrollable occurrences will be of such comparatively rare occurrence that the cost of protecting the service by loose linkage is unnecessarily great and not justified by the hazard.

As we develop extensive interconnection we are automatically driven toward loose linkage whether we like it or not. Overhead transmission lines will cut out under present-day conditions and with present-day equipment. The circumstances in each case must determine the extent to which running reserves will be operated and, therefore, the extent to which ideal loose linkage will be achieved.

**F. A. Allner:** Attention has been called in Mr. Downing's paper to the limitation or lessened desirability of interconnection when certain essential conditions favoring interconnection are absent. It should be recognized, to start with, that each case presents a problem controlled by the local conditions and that no generalization can be readily made. But it can be pointed out by an academic example that recent trends in power generation are working in favor of interconnection, even though certain obviously favorable factors are lacking, such as substantial diversity in load or in seasonal availability of power resources, or a pronounced differential in generating costs.

We may assume two systems, not interconnected heretofore, which have identical shapes of load curves, *i. e.*, no diversity of load, either in time of the year or hour of the day. We may also assume that the steam plants of the two systems are of nearly the same over-all economy. Under these conditions we should probably expect the least incentive for incurring a substantial investment for interconnection. However, the tendency in recent years to install large-size steam generating units, the capacity of which is equal to a large percentage of system load and considerably in excess of the annual increase of load demand, introduced several new elements in favor of interconnection, such as the staggering of investment steps between the two adjoining systems, savings in carrying charges on reserve equipment and more economical generation due to keeping on the line sufficient generating capacity only to compensate for the loss of one large unit instead of two. An interconnection of this sort has to be a solid tie (*i. e.*, not of the type referred to as loose linkage) which would insure that the two systems stay in parallel at times of transfer of maximum power coincident with short circuit on one tie line or with other system disturbances.

Mr. Gear's paper furnishes a practical example of the advantages incident to the staggering of investment steps involving three companies. It may be of interest to hear from him some further details as to the approximate capacity cost per kw. for which the three parties are billing each other.

In every case of interconnection particular stress should be laid on the quality of service, which feature has been brought out prominently in Dr. Hirshfeld's contribution. Quality of service should not suffer as a result of interconnection, allowing, of course, for the initial period of ironing our minor difficulties incident to the newness of the operating methods. The indirect consequences of impaired service may easily counteract any calculated economies that were originally the underlying reasons for interconnection. Most of us are familiar with the disastrous situation that may develop in a few minutes if two large systems or groups of a single system fall out of step due to major distribution trouble or other causes. As the frequency drops rapidly on that part of the system that has insufficient generating capacity connected to it, restoration of service usually involves the cutting off of a large part of the load and a considerable delay in resynchronizing.

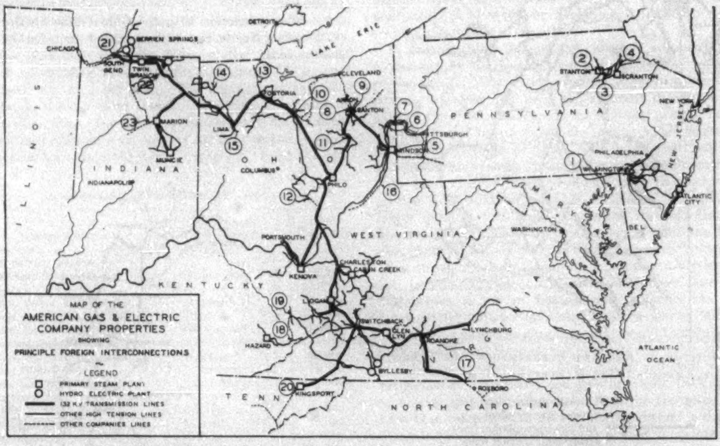

MAP OF THE
AMERICAN GAS & ELECTRIC COMPANY PROPERTIES
SHOWING
PRINCIPLE FOREIGN INTERCONNECTIONS
LEGEND
PRIMARY STEAM PLANT
HYDRO ELECTRIC PLANT
132 K.V. TRANSMISSION LINES
OTHER HIGH TENSION LINES
OTHER COMPANIES LINES
CHICAGO
BERRIEN SPRINGS
SOUTH BEND
TWIN BRANCH
MARION
MUNCIE
INDIANA
INDIANAPOLIS
ILLINOIS
DETROIT
LAKE ERIE
FOSTORIA
LIMA
OHIO
COLUMBUS
CLEVELAND
AKRON
CANTON
PITTSBURGH
WINDSOR
PHILO
PORTSMOUTH
KENOVA
WEST VIRGINIA
CHARLESTON
CABIN CREEK
KENTUCKY
LOGAN
HAZARD
SWITCHBACK
GLEN LYN
ROANOKE
LYNCHBURG
BYLLESBY
KINGSPORT
TENN
ROXBORO
VIRGINIA
NORTH CAROLINA
PENNSYLVANIA
STANTON
SCRANTON
NEW YORK
NEW JERSEY
PHILADELPHIA
WILMINGTON
ATLANTIC CITY
DEL
MARYLAND
WASHINGTON
ATLANTIC OCEAN
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Fig. 12—American Gas & Electric Company's Interconnected System
The points of interconnections and the capacity of interconnections are shown in Table I.

In connection with this problem it may not be amiss to point out a possible by-product of large-scale interconnection under certain conditions when a hydroelectric plant, possessing seasonal storage or pondage, can be tied into an interconnected system. Particularly in the case of low-head hydro-plants, units can be started up from standstill and synchronized in a small fraction of the time required for a steam unit, the total time for this operation being of the order of approximately one minute. As the customary types of waterwheel governors permit synchronizing adjustment down to a low range of speed, restoration of service can be accomplished without cutting off commercial load when such hydroelectric units are available for standby purposes. This quick starting ability of hydroelectric units has been referred to by the late Dr. Eglin as "the hydro a-c. battery service," comparable to a certain extent to the storage-battery service provided on large d-c. distribution systems.

Referring to Mr. Mitchell's paper, a question in connection with the forecasting of river flow may invite a statement of general interest regarding the success that Mr. Mitchell's engineers had in this line of work. Previous attempts of analyzing flow records on large streams over long periods, of the order of thirty to forty years, were not very successful, my recollection being that the cyclic equation was a different one for each period. It would be rather interesting to hear from Mr. Mitchell whether his forecasting has been found as satisfactory in other years than those shown on the chart.

**Philip Sporn:** (communicated after adjournment) The American Gas and Electric Company has operated an interconnected system for many years, in fact, interconnection on the American Gas and Electric Company system has grown up along with the system. In 1907, at Scranton, the company found itself with a shortage of capacity and the D. L. & W. Railroad, which was operating a plant in Scranton, found itself in the same predicament. The railway plant was furnishing power to a group of coal mines. An interconnection was worked out between them calling for interchange of capacity when and if available. Since the peak of the railway load was a morning peak, this interconnection made available considerable capacity for the lighting company to enable it to carry its evening lighting peak, and it, in turn, was able to help out the railway company on its morning peak.

Since then the American Gas and Electric Company's system has grown tremendously and as already stated, interconnection has grown with the system, in fact, whenever and wherever it was at all economically feasible to make an interconnection, it was made. Very often it was found that interconnections could be made at a rather small expense, but the benefits, based on advance analysis, were not quite apparent. The connections were made, nevertheless, on general principle in such cases and subsequent operation has always brought forth benefits far greater than were anticipated, so that we who have been working on interconnection, have come to believe that where an occasion for an interconnection presents itself, it is at least as rational, and probably more rational, to prove the case against interconnection rather than the other way around.

Fig. 12 herewith, shows the American Gas and Electric Company interconnected system as it is, including that portion of it that is actually under construction.

In Fig. 13 there is shown the Island of Great Britain, Scotland,

and Wales superimposed over the American Gas and Electric Company system.

In Fig. 14 there is shown a map of the British Isles with the central electric-supply scheme as recently outlined in the British Technical Press.[1] It will be seen from Figs. 13 and 14 that taking into account the width of the American Gas 132-kv. network, it is more extensive than the proposed network for Great Britain. A rough check of the distances involved in the network in the two cases may also be of interest. According to the best available data, the total length of lines in the proposed British network will be approximately 2500 mi. The total length of the American Gas and Electric Company system in miles is approximately 1227 and in circuit miles is approximately 1870. No data as to the total capacity that will be connected to the British network have been found available at the present time but it is doubtful that it will approach the capacity already connected to the American Gas 132-kv. grid, if the capacity of the interconnections is included.

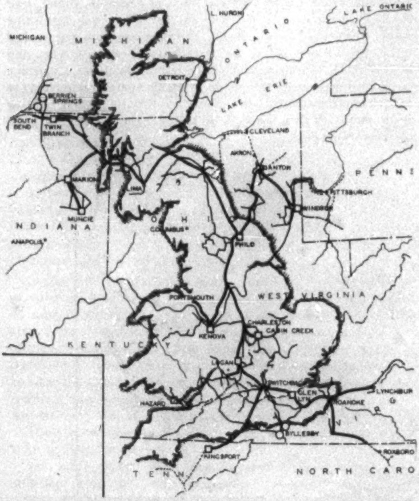
MICHIGAN
L. HURON
LAKE ONTARIO
ONTARIO
DETROIT
LAKE ERIE
BERRIEN SPRINGS
SOUTH BEND
TWIN BRANCH
CLEVELAND
AKRON
CANTON
PENNS
PITTSBURGH
WINDSOR
MARION
LIMA
MUNCIE
INDIANA
INDIANAPOLIS
COLUMBUS
OHIO
PHILO
WEST VIRGINIA
PORTSMOUTH
KENOVA
CHARLESTON
CABIN CREEK
KENTUCKY
LOGAN
SWITCHBACK
GLEN LYN
ROANOKE
LYNCHBURG
HAZARD
BYLLESBY
KINGSPORT
ROXBORO
TENN
NORTH CARO

Fig. 13—Outline of England Superimposed on Territory of American Gas & Electric Company

□ Primary steam plant
○ Hydro electric plant
━━━ 132 kv. transmission lines
──── Other high tension lines
- - - - - - Other companies lines

In Fig. 12 the extent to which interconnection has been carried out between various parts of the American Gas and Electric system and foreign companies is shown. It will be noted that including the system in New Jersey and Pennsylvania, there are 23 interconnections in actual operation, and the majority of them are 24 hours a day and 7 days a week interconnections. In other words, they are in parallel all the time.

The approximate capacity of these interconnections is 340,000 kw. The combined system peak of the interconnected American Gas and Electric companies at the present time is approximately 490,000 kw. The total primary generator capacity is approximately 543,000 kw. and the capacity, taking into account steam limitations, is approximately 503,000 kw. Including the stand-by capacity, that is steam capacity that is no longer used for daily carrying of load, the above figures are approximately 690,000 kw. and 565,000 kw. respectively.

It will at once be noted that this does not allow very much leeway in primary capacity for one or two big units being down but this is exactly where interconnection comes in. As illustrative of that, we may take an emergency condition that arose on the system last November when unit No. 1 at Philo (40,000 kw.) developed internal trouble and was taken out of service for inspection and repairs. Two weeks later, before unit No. 1 was replaced on the line, unit No. 2 (40,000 kw.) developed internal trouble and was removed from service, completely shutting down the Philo Plant and reducing the capacity of the system by 80,000 kw. It was not expected that unit No. 1 would be restored to service until the following week. This was on a Saturday, so that the system did not feel it at once but when the Monday load came on the interconnections were immediately pressed into service and the following arrangements made:

1. The connection with the West Penn Power Company (Connection No. 5, Fig. 12) was called upon for an additional 15,000 kw.

2. The connection with the Ohio Public Service Company (Connection No. 9, Fig. 12) was called upon for the maximum possible load.

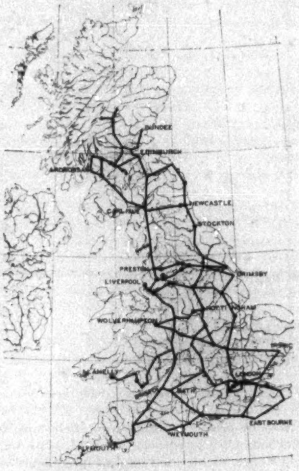
DUNDEE
EDINBURGH
ARDROSSAN
NEWCASTLE
CARLISLE
STOCKTON
PRESTON
LIVERPOOL
GRIMSBY
NOTTINGHAM
WOLVERHAMPTON
LLANELLY
LONDON
EAST BOURNE
WEYMOUTH
PLYMOUTH

Fig. 14—Simplified Map of Proposed English 132-kv. Grid Indicated in "The Electrician" Vol. 99, No. 2578, Page 546

● Primary Steam stations ▲ Hydro stations ━━ 132 kv. lines

3. The Cleveland Electric Illuminating Company (Connection No. 8, Fig. 12) was called upon and Cleveland responded with a promise of all that possibly could be carried on the 66-kv. cables between Lake Shore and Oak Street Substations, allowing approximately 50,000 kw. to feed in to Akron or approximately 30,000 above the normal amount.

4. The interconnection between the Southern Ohio Power Company and The Ohio Power Company at Haydenville (Connection No. 12, Fig. 12) was called upon for 5000 kw.

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[1] See *Electrician*, Vol. 99, No. 2578, pages 526 seq. and page 546.

5. The system south of the Ohio River was advised that not having been crippled it would have to take care of itself without any help from the north, calling upon its own interconnections if any help were needed.

6. Some of the minor interconnections were called upon for their quota.

The result of all this was that the interconnected system load of the American Gas and Electric Company subsidiaries north of the Ohio River was carried without the slightest disturbance on November 29 and until noon of November 30, when one of the Philo units was placed on to the line, and the load continued to be carried with a lesser call upon the interconnections until December 4 when the second unit came on the line. An important fact in connection with this is that no large quantities of energy were transmitted any long distance but demand was taken either directly into the American Gas and Electric system of a number of near points, or as in one or two cases the relief was obtained by a substitution process. For example, whereas the system normally supplies Akron from 20,000 to 30,000 kw. and Cleveland does the same, the coming in of Cleveland with an extra amount equal to their normal or approximately a total of 50,000 kw., made it unnecessary for the American Gas and Electric system to feed the usual amount to Akron.

On the question of diversity, it may be interesting to offer some figures. As stated, the system peak is approximately 490,000 kw. During the peak, the diversity between the interconnected companies, sub-dividing them into only four groups,[2] is approximately 15,000 kw. or 3 per cent. The diversity on the other hand, between the American Gas and Electric system and the Chicago system, due to the different characters of the loads and due to one hour difference in time, is far greater and is in the order of 60,000 kw. In other words, 60,000 kw. under the most unfavorable conditions could be sent by[3] American Gas and Electric interconnected system into the Chicago District, and Chicago could send a considerable amount in excess of that in a reverse direction.

FOREIGN INTERCONNECTIONS

| No. | Foreign Company | Point of Interconnection | Kw. Capacity |
|---|---|---|---|
| | *Atlantic City Electric Co.* | | |
| 1 | Delaware Electric Power Co. | Wilmington | 8000 |
| | *Scranton Electric Co.* | | |
| 2 | Penn. Power & Light Co. | Stanton | 50,000 |
| 3 | Penn. Power & Light Co. | Pittston | 4,000 |
| 4 | Penn. Power & Light Co. | Peckville | 15,000 |
| | *The Ohio Power Co.* | | |
| 5 | West Penn. Power Co. | Windsor | 90,000 |
| 6 | West Penn. Power Co. | E. Liverpool | 2,000 |
| 7 | Duquesne Light Co. | South Ferry | 2,000 |
| 8 | Northern Ohio Power & Light Co. | Canton | 30,000 |
| 9 | Ohio Public Service Co. | Canton | 15,000 |
| 10 | Ohio Public Service Co. | Shelby | 10,000 |
| 11 | Northern Ohio Traction Co. | New Phila. | 3,000 |
| 12 | Southern Ohio Power Co. | Haydenville | 5,000 |
| 13 | Toledo Edison Co. | Pemberville | 10,000 |
| 14 | Defiance Gas & Electric Co. | Auglaize | 3,000 |
| 15 | Western Ohio Railway Co. | Lima | 3,000 |
| | *Wheeling Electric Co.* | | |
| 16 | West Penn. Power Co. | St. Marys | 6,000 |
| | *Appalachian Electric Power Co.* | | |
| 17 | Carolina Power & Light Co. | Danville | 15,000 |
| | *Kentucky and W. Va. Power Co.* | | |
| 18 | Consolidation Coal Co. | Fleming | 3,000 |
| 19 | Consolidation Coal Co. | Martin | 5,000 |
| | *Kingsport Utilities, Inc.* | | |
| 20 | Tennessee Public Service Co. | Kingsport | 15,000 |
| | *Indiana & Michigan Electric Co.* | | |
| 21 | Northern Indiana Public Service Co. | New Carlisle | 40,000 |
| 22 | Northern Indiana Power Co. | Plymouth | 3,000 |
| | *Indiana General Service Co.* | | |
| 23 | Northern Indiana Power Co. | Sweetser | 4,000 |

In conclusion, we can say that it is our belief as a result of experience with an interconnected system and with interconnections with foreign companies extending over many years, that in addition to the many benefits of interconnection that have been so well stated in the papers under discussion, there is a number of points that are generally not brought out and these are:

1. Interconnection is a logical outgrowth of the development of the power industry. In most cases where the possibility of interconnection presents itself it is at least as rational to investigate the reasons against the interconnection as to assume that the interconnection has to be proved.

2. The actual benefits of interconnection will in the long run surpass the anticipated benefits.

3. As a general rule it will be found that the maximum benefit of an interconnection can be obtained under those conditions where power can flow back and forth or where a multiplicity of interconnections is involved, where an opportunity presents itself for substitution of energy from one point to the next and not by a direct transmission from any one extreme point of the system to the other.

**P. Junkersfeld:** (communicated after adjournment) Interconnection in the electric power industry was used as a part of the earliest networks, and later, beginning about 1890, to connect together d-c. networks adjacent or very near to each other for mutual assistance in maintaining approximately proper voltage at and near such points. Soon after, larger mains and then special feeders or trunk lines were used, and as soon as alternating systems and prime movers were sufficiently developed to be kept continuously and satisfactorily in synchronism under service conditions, interchange of energy took place in much larger quantities between generating stations directly, or indirectly by shifting of substation loads from one transmission line to another. It soon became necessary to have a single continuous operating agency to coordinate electrical operation, and in most instances the individuals have been called load dispatchers, and were first referred to before the A. I. E. E. incidentally in a paper presented by the writer in 1901.

Interconnections as generally understood today are maintained between different large elements of any one public-utility system, and between adjacent systems under different ownership or management to a greater and greater extent, both as to quantity of energy and as to distance. Most of the many advantages have been referred to in the various papers and in the discussions. These interconnections are usually a great operating convenience, and result in better service.

There seems to be a tendency sometimes to install such interconnections where the distance and other conditions affecting cost are such that the expenditure may not be justified by the noncoincidence of the peak loads or by the difference in generating costs on the two systems to be interconnected, or by the reduction in reserve generating capacity or by other factors. The interchange of too large a proportion of the energy required on one of two systems to be interconnected may not be profitable, or be less profitable solely as a matter of reducing generating costs than the interchange of a smaller proportion at the much higher load factor that may thus become available.

Instances like the foregoing have, however, heretofore been the exception. In the majority of interconnections the expenditure is amply justified by the many investment and operating advantages already referred to in some of the various papers and discussions. One additional illustration is the interconnection between the San Joaquin and Great Western systems in California, where a 100-mi., 165-kv. interconnection released about 20,000 kw. because of the diversity between these two systems. The sum of the two peaks on these systems was 267,000 kw. in 1926.

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[2] Appalachian Electric Power Company and subsidiaries: Ohio Power Company and Wheeling Electric Company; Indiana & Michigan Electric Company; Indiana General Service Company.

[3] Upon the completion of the Philo-Fostoria line now under construction.

The trend to operate the most economical sources of steam or hydroelectric power at larger and larger annual load factors and better continuity of service seems to indicate an increasing number of interconnections between systems, and with properly developed load dispatching frequently affords opportunity to reduce total generating costs and also to improve the service rendered to the public.

**W. A. Naudain:** (communicated after adjournment) Mr. Mitchell states that on a system combining run-of-river and storage hydroelectric plants and steam plants, great savings can be made by accurate knowledge of river flows. Also careful study is being given to this by all large systems, and what the subsidiaries of Southeastern Power and Light Company have done, is typical of the other companies.

If the United States Geological Survey which is primarily interested in the making of maps, could be impressed with the value of this information to the utility companies, they might be induced to include this—furnishing these data in connection with their map data, with very little additional work to themselves.

Also the Corps of Engineers of the several geographic divisions, who are to such a large extent connected with and interested in river flows might in connection with their regular work, supply these data for public utility benefit. This would result in making river data available to the utility companies without the resultant expense, which is a product of such a survey.

**N. E. Funk:** I should like to say that I agree thoroughly with Mr. Lee. I think the shorter our transmission lines are, the closer we can build our generating stations to our load, the better off we will be.

I say that because with this 220-kv. interconnection, it may look as though we are following the diametrically opposite course.

The 220-kv. interconnection is rather unusual in that there is a very decided diversity in the loads concerned. Starting with the first section of the interconnection, the line between Siegfried and Plymouth Meeting, where about 50,000 kw. can be used, only as emergency because of the fact that there is only one line, the load will build up over 200,000 kw. interchange between morning and evening. A case like this is not so often found, and occurs only in this case because of the entirely differently shaped loads in the territories connected.

**W. E. Mitchell:** I will answer Mr. Allner's question first, as to how far back the forecasting goes. We only worked it out three years ago, therefore we had only three years to check it in. We have made our forecast for the next three years.

I may say, we think the cycle is too short. If we could get a cycle of two hundred years or two thousand years, we might know something about the rainfall and prognosticate about its cyclic variation. As it is, we are making a good guess and the method of arriving at the guess is simple and very interesting.

Now in the matter of interconnection, I am glad we are getting out of the intellectual and technical field. We are getting down to plain common sense. As Mr. Edgar has said, it is a matter that is inevitable but it isn't going to cure all sorts of troubles. Mr. Lee has hit the nail on the head. We are interconnecting where it is economically wise and we are trying to get the load and the place where the power is made closer together. After that, interconnection pretty nearly takes care of itself in the matter of improvement to service, and the reduction in idle plant capacity. Undoubtedly there is entirely too much of that all over the country today, capacity that isn't earning a dollar for any of us, and yet which with isolated properties was essential for the protection of service. After all, it is service we are selling. We can reduce that idle capacity and therefore reduce the cost of that service through interconnection wisely developed.

**H. B. Gear:** Replying to Mr. Allner's request for a statement of the basis of charge between the companies in the Chicago District, the amount paid consists of three parts,

(a) the capacity charge,
(b) the regular energy charge, and
(c) the surplus energy charge.

The capacity charge is paid by any company deficient in capacity or reserve, and consists of fixed charges on generating-station capacity, step-up transformers, and interconnecting lines.

The regular energy charge consists of the cost of producing and delivering the kilowatt-hours taken by any company under its deficiency requirements.

The surplus energy charge consists of charges directly proportional to kilowatt-hours (chiefly fuel) for energy taken at off-peak hours, for the purpose of realizing the advantage of lower production costs in the neighboring station than can be realized at stations in the zone where the energy taken is utilized.

It is the intent that the most economical units will be working at their highest practicable load at all hours.

# Saturation Permeameter

BY S. L. GOKHALE[1]

Member, A. I. E. E.

***Synopsis.**—The saturation permeameter is a device for speedy and accurate measurement of saturation value of magnetic material; that is, for measurement of the limiting value of intrinsic induction ($\beta$) characteristic of that material. The permeameter in its present form is of the well-known bar-yoke type, with a magnetizing coil capable of producing a magnetizing force of $H$ = 4500 g. without excessive heating. The permeameter is equipped with a compensating coil whose function is to compensate automatically for the spatial flux enclosed by the potential coil, so that the ballistic deflections indicate the saturation value without further computation or correction. The permeameter is available for accurate measurement of saturation value of such material as is saturated well within the working range of the permeameter, i. e., with a magnetizing force of $H$ = 3000 g., or less, which includes all magnetic material used for electrical engineering purposes except those for permanent magnets and cobalt. The saturation permeameter is also available for approximately correct measurement of $B$ or $\beta$, for range of $H$ below the saturation point as far down as $H$ = 200 g. In speed of testing and accuracy of the measured saturation value, this permeameter surpasses all devices for saturation measurement developed heretofore.*

THE following symbols are used in this paper with the corresponding unit stated in brackets:

| | |
|---|---|
| $B$ | Total induction or flux density (gauss). |
| $\beta$ | Intrinsic induction $(B - H)$ (gauss). |
| $H$ | Magnetizing force (gilbert per cm.; briefly g.). |
| $H$ | Spatial induction (gauss). |
| $\lambda$ | Interlinkage (Maxwell). |
| $I$ | Magnetizing current (ampere). |
| $S$ | Saturation value; *i. e.*, limiting value of $\beta$. |
| $A$ | Cross-section of space enclosed by potential coil. |
| $a$ | Cross-section of material under magnetic test. |
| $n$ | Number of turns of potential coil. |
| $M_c$ | Mutual inductance of the compensating inductor. |
| $H/I$ | $H$-factor of the permeameter. |
| $H_s$ | Saturation point; *i. e.*, the value of $H$ at which $\beta$ reaches the constant value $S$. |
| $\mu_i$ | Intrinsic permeability, $(B - H)/H$, or $\mu - 1$. |

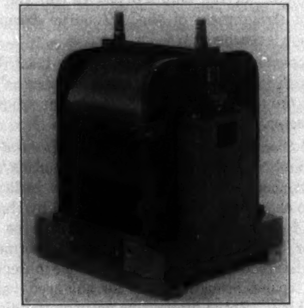

FIG. 1—SATURATION PERMEAMETER

The symbol $H$ is ambiguous, but the ambiguity causes no inconvenience and is therefore left uncorrected.

METHOD OF TEST

For scheme of wiring see Fig. 2. The compensating inductor which is a variable mutual inductor $M_c$ is adjusted to the required value approximately to start with, and exactly by trial as the test progresses. The permeameter is then treated like the ordinary bar-yoke permeameter, using magnetizing currents ranging from 5 to 30 amperes. If the upper part of the magnetization curve thus obtained appears to be straight over a considerable range, after making a reasonable allowance for stray points, it is assumed that the sample is really saturated for that range. The compensator is then adjusted by trial until the deflection for the supposed saturation range appears to be strictly constant. The constant value of $\beta$ thus indicated is accepted as the true saturation value. The lower part of the magnetization curve is theoretically not reliable, but it has been observed that for magnetizing forces as low as $H = 200$ g., the $\beta H$ curve by the saturation permeameter is in very close agreement with the corresponding part of that curve by the Bureau of Standards compensation method (Fig. 3). This value of magnetizing force ($H = 200$ g.) is therefore accepted as the lower limit of reliability of the saturation

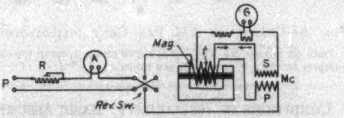

FIG. 2—WIRING DIAGRAM FOR DETERMINATION OF SATURATION

This illustrates the compensation method. It is also the connection used with slight modification in testing the range of reliability of the instrument

$P$ = Source of power, direct current
$R$ = Control rheostat
$A$ = Ammeter
Mag. = Magnetizing coil of saturation permeameter
$t$ = Potential coil for measurement of $\beta$
$H'$ = Coil for measurement of $H'$ located in the space between the test sample and the inner surface of the magnetizing coil (not shown in this diagram; used for test in paragraph 5, Fig. 4)
$M c$ = Mutual inductor—variable for compensation
$P$—Primary coil
$S$—Secondary coil
$G$ = Galvanometer

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[1] General Engineering Lab., General Electric Co., Schenectady, N. Y.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., February 13-17, 1928.*

permeameter, although in some cases the agreement may reach down to lower magnetizing forces (Fig. 6).

## DETERMINATION OF *H*-FACTOR

The function of the compensating inductor is to compensate for the spatial flux enclosed by the potential coil of the permeameter. When the compensation is exact, as shown by the constancy of the indicated value of $\beta$, the interlinkage of the secondary coil of the inductor must be equal to the spatial interlinkage of the permeameter. Expressed analytically, we have the equation

$$\lambda s = \lambda c$$

or, $$H\, n\, A = M_c I / 10$$

where $\lambda_s$ is the spatial interlinkage of the potential coil of the permeameter,

$\lambda_c$ is the interlinkage of the secondary coil of the compensator.

Then, the *H*-factor of the permeameter is

$$H/I = M_c / 10\, n\, A$$

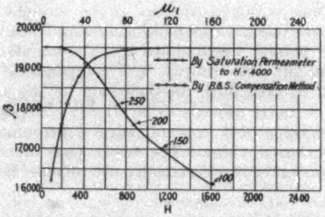

FIG. 3—CURVES OF 2½ PER CENT SILICON-STEEL SHEET

Tests on sample No. D-7. $\beta\, H$ curve and $\beta\, \mu_i$ curve are shown. The numbers on the $\beta\, \mu$ curve indicate values of *H*

## CONDITIONS OF RELIABILITY; BASIC ASSUMPTIONS

When the compensation is exact, as indicated by the constancy of the observed ballistic deflection, the interlinkage under measurement is constant; hence we have the equation

$$\beta\, n\, a + H\, n\, A - M\, I/10 = \lambda_s = \text{constant}$$

where $\lambda_s$ is the value of the total interlinkage measured,

$\beta\, n\, a$, interlinkage of intrinsic flux,

$H\, n\, A$, interlinkage of spatial flux,

$M\, I/10$, interlinkage of compensating inductor.

By differentiation with relation to *I*, we get

$$n\, a \cdot \frac{d\beta}{dH} \cdot \frac{dH}{dI} + n\, A \cdot \frac{dH}{dI} - M/10 = 0.$$

$$d\beta / dH = (M/10 - n\, A \,.\, dH/dI)/(n\, a \,.\, dH/dI)$$

*Assumption I.* Assuming that the *H*-factor of the permeameter is constant for the range under consideration, we have the equation

$$H/I = C$$
$$dH/dI = C$$

Substituting this value in the above equation, we get

$$d\beta/dH = (M/10 - n\, A\, C)/n\, a\, C$$
$$= \text{constant}$$

*Assumption II.* At this point, a further assumption is made, *viz.*, that if $d\beta/dH$ is constant, the value of the constant is zero. Graphically, it is assumed that if any extensive part of the $\beta\, H$ curve be straight, it is at the same time also parallel to the axis of *H*. In other words, it is assumed that no large part of the $\beta\, H$ curve is straight without being parallel to the axis of *H*. With this assumption, the above equation is reduced to the two equations,

$$d\beta/dH = 0; \text{ and } n\, A\, C = M/10.$$

From the first equation we get

$$\beta = \text{constant}$$
$$= S; \text{ (saturation value)}$$

From the second equation we get

$$H\text{-factor} = C = M/10\, n\, A$$

The reliability of these two measurements depends upon the validity of the assumptions (1) constancy of the *H*-factor for the required test range; and (2) absence of straightness of the $\beta\, H$ curve except when saturation is reached.

The constancy of the interlinkage by itself does not carry with it unconditionally the assurance of saturation, or the accuracy of the measurement of *S*, or of the *H*-factor. The equation

$$d\beta/dH = (M/10 - n\, A \,.\, dH/dI)/(n\, a \,.\, dH/dI)$$

might hold true when neither $dH/dI$ nor $d\beta/dH$ are constant, because it may be that the variations in $\beta$ due to changes in *H* might be balanced by changes in *H* due to variations of *H*-factor. It can be shown, however, that in the case of the saturation permeameter under discussion, the constancy of the observed deflection is not brought about by balanced variations of this kind. Space limitations prevent the discussion of the proof of this point.

*Validity of Assumption I.* There has been no method discovered for direct measurement of *H* at a point in the test sample, and not even for indirect measurement, except under certain favorable conditions which are not present in this case. But the value of *H* at a point inside of the magnetizing coil and in close proximity to the sample can be easily measured by ballistic determination of spatial flux near that point. (For test data see Fig. 4.) A study of the curves shows that the *H*-factor for the proximate space is practically constant, the deviation from constancy ($\Delta\, \theta/\theta$) being undetectable for $I = 5$ to 20 amperes and less than one part in 1000 for the range $I = 3$ to 29 amperes. On the basis of this observation it seems reasonable to assume that the *H*-factor in the body of the sample is also constant within the same limits, because the causes that tend to produce deviation in the one case are also the only possible causes operative in the other case. It is therefore assumed that in the case of this saturation permeameter, the *H*-factor is strictly constant for values of *I* between the limits 5 to 20 amperes ($H = 750$ to 3000 g.) and almost constant for $I = 3$ to 29 amperes ($H = 500$ to 4000 g.).

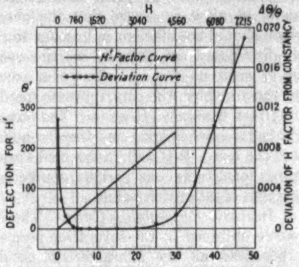

FIG. 4—H-FACTOR CURVE AND PRECISION LIMITS

*Validity of Assumption II.* The second assumption underlying the compensation method is, that no part of the $\beta H$ curve is straight without being parallel to the axis of *H* at the same time. Stated analytically the assumption is that $d\beta/dH$ is not constant but varies with *H*, except when it (*i. e.*, $d\beta/dH$) becomes zero. The assumption is supported by numerous tests on magnetic material of various kinds, tested in the form of toroid rings to preclude uncertainty due to possibilities of error inherent in other methods of test. It was found in all these cases that the $\beta H$ curve was not straight until the saturation point was reached, after which point the curve was straight and parallel to the axis of *H*. In no case was a large part of the curve straight without being parallel to the axis of *H*.[2] In order to submit the matter to a more severe test, one toroid ring was tested by the differential test. (See Fig. 5.) In this case the value of $\Delta\beta/\Delta H$ is not constant until it is reduced to zero. All reliable data thus far are in support of the Assumption II, and there are none to contradict it.

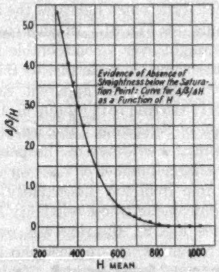

FIG. 5—CURVATURE OF $\beta H$ CURVE BELOW SATURATION

The curve is for $\Delta\beta/\Delta H$ as a function of *H*. Standard sheet-steel toroid rings used with compensation for spatial flux

Examples of apparent exceptions are given in paragraph on Form of Intrinsic Permeability Curve (see Incidental Observations).

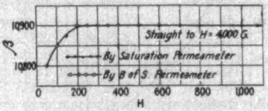

FIG. 6—$\beta H$ CURVES FOR PERMALLOY ROD

Limit of Error, ± 2½ gausses

*Experimental Evidence of Reliability.* Fig. 6 represents the $\beta H$ curve for a sample of permalloy by the saturation permeameter, this sample being selected for the reason that it can be saturated by a magnetizing force of $H = 200$ g., which permits its saturation value to be determined by the Bureau of Standards compensation method, whose reliability has been accepted as indisputable. The close agreement of the two $\beta H$ curves by the two methods constitutes a very persuasive argument as to the reliability of the saturation permeameter. This experiment disproves the balanced compensation referred to in paragraph on Conditions of Reliability and confirms the validity of the two basic assumptions. Full discussion cannot be given in this paper.

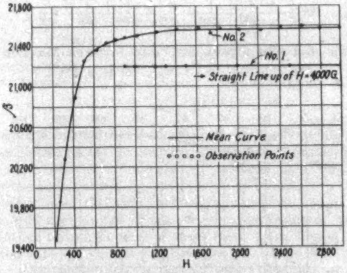

FIG. 7—SATURATION OF PURE IRON

Curve 1 was taken by the saturation permeameter; curve 2, by the Bureau of Standards isthmus permeameter. Curve 1 shows the absence of stray points by the saturation test

*Internal Compensation.* For further simplification of test procedure a small coil of sufficient interlinkage-coefficient, located in the proximate space, may be used in place of the compensating inductor. This method of compensation has the advantage of simplifying the test procedure, as the adjustment is made once for all and needs no further consideration.

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[2] Gokhale, Sept. 1926, p. 853, et. seq.

## INCIDENTAL OBSERVATIONS

*Absence of Stray Points.* The saturation part of the $\beta H$ curve by the method outlined herein is free of stray points. This is due to the fact that the ballistic deflections for this part are not dependent on the exact value of the magnetizing current; any error in reading the ammeter has therefore no effect on the deflection; all the observation points for this part of the curve fall on a straight line parallel to the axis of $H$. In this respect this method of test surpasses all other methods. (For comparison, see Fig. 7.)

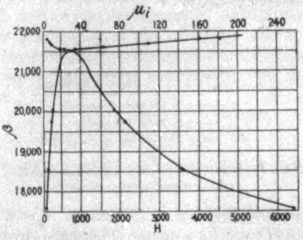

FIG. 8-1—$\beta\,\mu$ CURVE BY THE LONG-SOLENOID METHOD

This is the method of B. O. Peirce, Academy of Arts and Science, (Vol. 49-2, p. 139, Table 6)

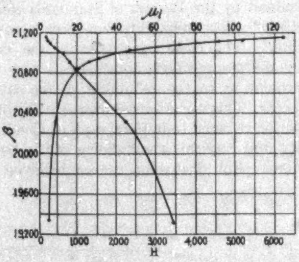

FIG. 8-2—$\beta\,\mu$ CURVE BY YOKE ISTHMUS METHOD

By Gumlich, *Arch. f. Elec.*, Vol. II, p. 471

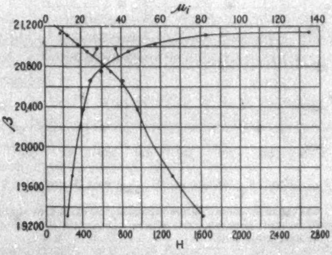

FIG. 8-3—$\beta\,\mu$ CURVE BY BUREAU OF STANDARDS ISTHMUS PERMEAMETER

By Cheney, Bureau of Standards. Paper No. 361, p. 633

*Speed of Test.* Since the accuracy of measurement of $S$ does not depend on the accuracy of the ammeter, it is needless to waste time in accurate adjustment or reading of the current. The only reason for reading the ammeter at all is to assure that the observation points which should be sufficient in number and reasonably well distributed are actually so: the operator is instructed to waste no time and effort over accuracy of reading of the ammeter; this contributes to speed of test.

*Freedom from Excessive Heating.* The rapidity of test prevents excessive heating and thereby adds to the accuracy of the test. It is well known that variation of temperature constitutes one serious source of error in measurement of saturation value.

*Form of Intrinsic Permeability Curve.* The form of the $\beta\,\mu_i$ curve obtained by the saturation permeameter (Fig. 3) possesses all the characteristic peculiarities of the curve, by the compensated toroid ring method described in the *Law of Magnetization.*[3] The corresponding curves by other methods of test do not generally possess that form which indicates the unreliability of those methods (see Fig. 8). In such cases only, the $\beta\,H$ curve is straight over a considerable range, without being at the same time parallel to the axis of $H$. These curves constitute the apparent exceptions to the *Assumption* II referred to in *validity of Assumption* I.

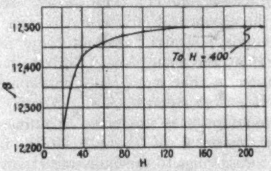

FIG. 9—SATURATION OF NICKEL-IRON ALLOY RING BY INCREMENTAL METHOD

Limit of Error, ± 2½ gausses

*Demonstration of Saturation.* Incidentally, we have now an experimental evidence of the phenomenon of saturation by a large number of tests on toroid rings, and therefore free from any uncertainty inherent in any type of permeameter whose reliability is unproved. In one case (see Fig. 9), the ring was tested by the method of increment which reduces the limit of observation error to ±2.5 gausses in $\beta$. In this case the variation of the curve from straightness—if there be any variation at all—does not exceed one part in 5000. This experiment therefore constitutes a convincing evidence of the phenomenon of saturation, and therefore also a confirmation of Weber's theory of molecular orientation.

*Limits to the Use of Saturation Permeameter.* The theory of the saturation permeameter implies two limitations to its use. First, the test sample must be capable of saturation well within the upper precision limit of the permeameter, *viz.*, $H = 4000$ g. (See Fig. 4.) For practical reasons $H = 3000$ is regarded as the upper limit. Magnetic material which does not reach saturation at this point, such as cobalt, cannot be successfully tested by this permeameter, for determination of saturation value. Second, the saturation permeameter is not theoretically available for accurate test much below the lower precision limit, (*viz.*, $H = 750$ g., see Fig. 4). But it has been observed in all cases that the curves obtained by this permeameter agree very closely with corresponding curves by the Bureau of Standards method, down to $H = 200$ g. (See Figs. 3 and 6.) This value of $H$ is therefore considered as the lower limit of practical reliability.

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[3] A. I. E. E., TRANS. 1926 Vol. 45, p. 1023 and Disc. p 1033, Figs. 4-0, 6-0.

### CONCLUSION

From the preceding arguments, data, and curves, it follows that the saturation permeameter is speedier and more reliable than all other types of apparatus used until now for determination of saturation value.

## Discussion

**W. B. Kouwenhoven:** I should like to know if the straight line relation between deflections for $H$ and magnetizing current $I$ for the range of 5 to 20 amperes of Fig. 4 of the paper will hold for all specimens tested. It would also be helpful if Mr. Gokhale would give additional data as to the size of specimens which the permeameter will hold, the number of turns, the size of wire, the resistance of the winding, and the dimensions of the device. These data will serve to make the paper more valuable.

The means for holding specimens in a permeameter are of importance as different results may be obtained by various clamping arrangements. The temperature of the specimen will also affect its magnetic characteristics and at high densities there is usually considerable heating. I should like to have Mr. Gokhale tell us something about the methods used for clamping specimens and about the temperature rise of specimens in his permeameter.

**Hans Lippelt:** The writer gives in his paper a quantity $H_s$ as representing the saturation point, *e. g.*, that value of $H$ at which $\beta$ reaches the constant value $S$. As is well known, this value of $H$ is, theoretically, infinitely large.

For practical purposes the distinction of being the saturation point may be assigned to a certain finite value $H_s$, with which, however, must be associated the fact that the coordinate value $\beta_s$ is only very near to the actual saturation $S$ of the material.

The definition of $H_s$ should then be qualified by the statement of a conventional "tolerance" $\dfrac{S - \beta_s}{S}$.

Furthermore, when determining the saturation point by the saturation permeameter, its sensitiveness and that of the galvanometer should be made known. In other words, it should be stated (a) either whether the new permeameter and other parts of the outfit are sensitive enough to record changes of $\beta$ at the magnetic limit set by the above tolerance, or else (b) what other tolerance determines the upper limit of the permeameter's ability.

In connection with the avoidance of excessive heating, of which the author speaks, it seems that the permeameter could be improved by using wire made of copper having super-conductivity. I understand the General Electric Company has developed such copper of superconductivity.

**S. L. Gokhale:** The straight-line relation of $H'$ to $I$, over a wide range of $H$, as indicated by the zero deviation over the range of $I$ from 5 to 20 amperes, or to express it more precisely, the constancy of the $H$-factor over that range, does not hold true for all material. We have found by measurement that it does not hold true for magnetic material in the hardened state, even when the sample is apparently saturated within the recognized upper working limit of the permeameter, *viz.*: $H = 3000$ to 4000 gausses. For example, Fig. 1 herewith is the apparent $\beta$ $H$ curve for two bars of magnet steel indicating a saturation value of $\beta = 17{,}000$ and 16,900 gausses respectively, and a saturation point of $H_s = 2500$ *g.* But the corresponding deviation curve, Fig. 2 herewith, is not straight which makes the saturation measurement unreliable. As far as we know until now, the failure of the saturation permeameter is limited to material for permament magnets. The deviation curve is straight over a wide range for all other material used for electrical engineering purposes in our work. These facts have been stated clearly but very briefly in the synopsis.

With reference to permanent magnets, we have found moreover, that by using a sample of smaller cross section we can obtain the corresponding deviation curve with lesser curvature. Further work in this direction is in progress. From the above observation it follows that if a sample of any material falls within the class for which the permeameter is reliable, a smaller sample of the same material will also fall in the same class. This conclusion has been verified by observation by testing two samples of the same material of very unequal cross sections.

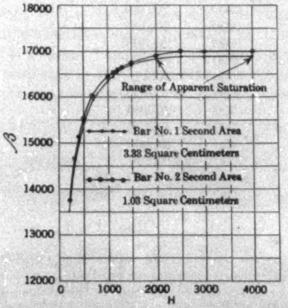

FIG. 1—TUNGSTEN MAGNET STEEL, MAGNETIZATION CURVES BY SATURATION PERMEAMETER

With reference to size of sample, this permeameter was first designed for testing bundles of sheet steel, 3 cm. broad, 25 cm. long, and about ½ cm. thick, (16 strips of 0.014 in. sheet steel). It was subsequently used for testing fewer strips down to single strips and has proved satisfactory in every case. The permeameter has been used for testing flat bars and has proved satisfactory for this purpose also except, of course, in the case of permanent-magnet material.

By using auxiliary pole shoes, the permeameter has been adapted for round rods of 6 mm. diameter, and has proved quite reliable for this purpose. A second permeameter has been constructed for testing round rods of ½-in. diameter; it is also reliable for all material except permanent-magnet steel.

With reference to clamping, it has been observed that variation due to faulty clamping is very slight, and consists of error in the indicated value of the saturation point $H_s$; it does not affect the saturation value. In one case on record the insertion of one thickness of tissue paper did not affect either of the two readings;

the insertion of a thicker paper apparently increased the value of $H_s$, but not of $S$. It follows from this that slight variations in clamping such as will occur in every-day work without exceptional carefulness, lead to no error at all in the measurement of $S$, and practically no error in the $\beta$ $H$ curve below saturation.

With reference to heating, I should have called attention to what looks like a pair of horns on the top of the permeameter (see Fig. 1 in the paper). The permeameter is provided with a cooling chamber into which is forced a blast of cold air through one of these horns, the other being used as an outlet. This method of cooling combined with the speed of testing possible with this permeameter, permits an accurate determination of saturation value with a rise of temperature of the sample not exceeding 1.6 deg. cent. The following is a sample of a complete test:

Standard Sheet Steel 0.014 in.
Tested with Saturation Permeameter

| $H$ | $\beta$ | Temp. |
|---|---|---|
| 4000 | 20,600 | 28.5 deg. cent. |
| 3000 | 20,600 | |
| 2500 | 20,600 | |
| 2000 | 20,600 | |
| 1500 | 20,600 | |
| 1300 | 20,550 | |
| 1200 | 20,525 | |
| 1000 | 20,500 | |
| 900 | 20,470 | |
| 800 | 20,425 | |
| 700 | 20,400 | |
| 600 | 20,300 | |
| 500 | 20,150 | |
| 400 | 19,800 | |
| 300 | 19,200 | |
| 200 | 18,300 | |
| 100 | 17,050 | 30.1 |

Rise 1.6 deg. cent.

In attempting to reach higher values of $H$ with the permeameter, the real difficulty lies not in producing the higher values of $H$, but in the accurate measurement of the values so produced. A reference to Fig. 4 of the paper will show that in that particular case we have actually reached a value of $H = 7200$ $g$., that is, 75 per cent above the regular upper limit, but at this point the deviation of the $H$-factor from constancy is nearly 2 per cent, which is fatal to the reliability of the permeameter. Until this difficulty is surmounted, it is no use trying to force $H$ to higher values by any means.

The desirability of more data is indisputable; in fact they were included in the paper when it was first prepared, but were subsequently omitted for convenience of publication. Such information will be sent to any one who chooses to go deeper into the subject.

With reference to Mr. Lippelt's question, it is not clear to me what theory he has in mind. Personally, I know of no well established theory which calls for a slow and gradual approach of the $\beta$ $H$ curve to the saturation limits. On the contrary, I have a strong bias in favor of the view that as saturation approaches, the $\beta$ $H$ curve deviates from whatever law it follows up to then, and rapidly reaches the saturation limit and then by an abrupt change follows the saturation line. I confess frankly that it is merely a bias at present, but it seems to be a very reasonable hypothesis.

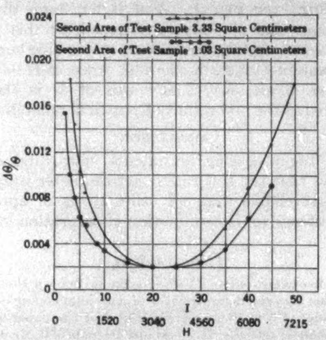

Fig. 2—Deviation Curve for Tungsten Magnet Steel

Leaving aside the theoretical aspect of the question and dealing with the subject in its practical aspect, the point $H_s$ is defined as that value of $H$, for which the corresponding value of latent induction $\gamma$, that is, $S - \beta$, is less than the least detectable value under the condition of test. For example, in Fig. 6 the value of error is only 2½ gausses. In every case the limit is determined by the sensitivity of the galvanometer used for the particular occasion.

# Compressed Powdered Permalloy
## Manufacture and Magnetic Properties

BY W. J. SHACKELTON[1] and I. G. BARBER[2]
Associate, A. I. E. E. Non-member

***Synopsis.***—*The paper gives a brief description of the manufacture of magnetic cores of compressed permalloy powder followed by information covering their magnetic properties with particular reference to their use in loading coils. Production of the powder, and its insulation, pressing, and annealing are discussed. Under magnetic properties, permeability, core loss, and modulation are treated. Curves are given illustrating the characteristics of interest in connection with the design and application of loading coils; and comparisons to corresponding characteristics of compressed powdered iron are made throughout.*

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### INTRODUCTION

It is now somewhat over ten years since commercial use was first made of loading coils having cores of compressed powdered iron. During this period all but a relatively small percentage of the loading coils produced for the Bell System have been of this type. The general construction of these coils, the practises employed in their application to the telephone plant, and the theory underlying these practises have been thoroughly discussed in previous papers.[3,4,5] The distinguishing feature of these coils that is of interest in connection with the present subject is the type of magnetic material used in their cores, namely, compressed powdered iron. The iron used for this purpose is electrolytically deposited in such a manner as to be readily reducible to a fine powder. This powder, after its particles have been coated with a suitable insulating film, is formed, under high pressure, into rings of approximately rectangular cross-section. One or more of these rings may be used to form a complete toroidal core, in the manner shown in Fig. 1. The method of manufacture and the properties of such compressed, powdered iron cores were described by Buckner Speed and G. W. Elmen[6] in a paper presented before the Institute in 1921.

Some years ago a nickel-iron alloy, particularly valuable for its magnetic properties, was developed.[7] This alloy, known as permalloy, was described by Arnold and Elmen[8] in 1923. Permalloy is especially adapted to many uses in the realm of communication, on account of the fact that its permeability at low fields is many times higher than for any other known, magnetic material. Until recently this material has, however, been fabricated only in the form of ductile sheets that could be blanked to various shapes for use in such telephone apparatus as relays and transformers, or in the form of wire or tape that could be applied to the continuous loading of submarine telegraph cables.

On account of the low hysteresis loss that is characteristic of permalloy, its application to the cores of loading coils seemed desirable. In the sheet or tape form, the material is not particularly adapted to this purpose. As was discussed in the Speed-Elmen paper,[6] such cores must meet the following rather severe electrical and magnetic requirements:

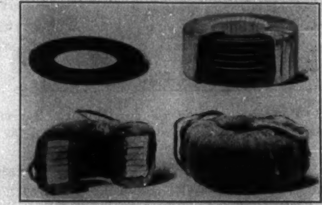

FIG. 1—COMPRESSED POWDERED IRON CORE LOADING COIL

1. The permeability must remain constant over the range of magnetic induction corresponding to the normal range of telephone currents, and it must always return to very nearly its original value after the application of large magnetizing forces.
2. Modulation effects caused by hysteresis must be small.
3. The total of the hysteresis and eddy-current losses must be low.

To satisfy these requirements it is necessary to have the cores operate at low magnetic inductions, a condition which is most readily fulfilled by the use of compressed powdered materials. This type of core affords, in addition, an economical means of obtaining the fine subdivision required to keep eddy-current losses at a minimum. Early attention was directed toward the possibility of fabricating permalloy into a powder, and of insulating and forming this powder, under high pressure, into core parts.[9] Many difficult problems have been encountered in this work; and it was only after a large amount of experimental development that the method now in use for commercially attaining this end was evolved. The present paper describes this method and discusses the important, characteristic properties of such compressed, powdered permalloy cores.

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[1] Bell Telephone Laboratories, Inc.

[2] Western Electric Company, Inc.

[3] *Wave Transmission over Non-Uniform Cables and Long Distance Air Lines*, M. I. Pupin, TRANS. A. I. E. E., Vol. 17, 1900, p. 445.

[4] *Commercial Loading of Telephone Circuits in the Bell System*, B. Gherardi, TRANS. A. I. E. E., Vol. 30, 1911, p. 1743.

[5] *Development and Application of Loading for Telephone Circuits*, Thomas Shaw and William Fondiller, TRANS. A.I.E.E., Vol. 45, 1926, p. 268.

[6] *Magnetic Properties of Compressed Powdered Iron*, Buckner Speed and G. W. Elmen, TRANS. A. I. E. E., Vol. 40, 1921, p. 596.

[7] U. S. Patent 1586884, June 1, 1926, G. W. Elmen.

[8] "Permalloy, An Alloy of Remarkable Magnetic Properties," H. D. Arnold and G. W. Elmen, *Jl. of the Franklin Institute*, Vol. 195, No. 5, 1923.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., February 13-17, 1928.*

## MANUFACTURE

*Manufacture of Permalloy Powder.* The first part of the problem, to develop a method for economically manufacturing on a large scale the fine alloy powder, was undertaken and solved by the engineers of the Western Electric Co. Experiments were directed to the production of a brittle, grindable alloy with particular reference to the effects of the melting practise and the subsequent working of the cast alloy ingot. This work, due largely to C. P. Beath and H. M. Heinicke, has lead to the establishment of a melting and rolling practise by means of which the permalloy can be made so brittle that strips ¼ in. thick can be easily broken by hand. Such brittle material is easily reducible to a fine powder by means of a hammer mill, a ball mill, or attrition mill. Fig. 2 shows a photomicrograph of a properly rolled slab. The fine crystals and the fracture following the crystal boundaries are to be noted.

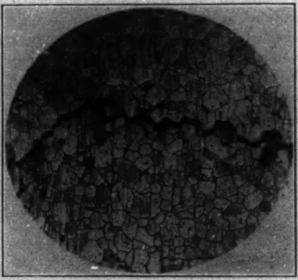

FIG. 2—PHOTOMICROGRAPH OF HOT-ROLLED BRITTLE PERMALLOY. MAGNIFICATION APPROXIMATELY 66

This method of producing permalloy powder has been applied to nickel-iron alloys ranging from 70 per cent to 90 per cent nickel. The permalloy, used for the cores discussed in this paper, contains approximately 80 per cent of nickel, as with such a composition the low hysteresis loss and high magnetic stability desired for loading coil cores are best obtained simultaneously.

*Manufacture of Compressed Powdered Permalloy.* Cores made from uninsulated permalloy powder have high eddy-current losses, thus making it necessary to insulate the individual particles before pressing. Early attempts at doing this were unsuccessful, partly due to the fact that the particles, hardened by the mechanical working in the ball mill, sheared through the thin film of enveloping insulation during the pressing operation. In order to reduce this shearing action it was found advantageous to soften the powder by annealing it before insulating. This annealing also has a desirable effect upon the hysteresis loss. During the annealing operation, the powder sinters together into a hard cake. This cake, however, is easily reducible to powder again by passing it through a rotary crusher and an attrition mill. The resulting annealed powder is of a silvery white color and contains a wide variety of sizes of particles. Fig. 3 shows a characteristic distribution of particle sizes in annealed permalloy powder.

The next part of the problem encountered, that of insulating the permalloy powder, was decidedly more complex than for compressed, powdered iron cores, as insulated powdered permalloy cores must withstand a heat treating operation in order to develop their characteristic properties. This is largely necessitated because of the detrimental effects produced by the high pressure used in forming the core parts. As the temperature of this heat-treating operation is above that at which the ingredients that would ordinarily be used for this purpose lose their insulating properties, it was necessary to develop a radically new kind of insulator. The fineness of the powder also required that this insulator be of extreme thinness in order to obtain in the compressed aggregate a specific gravity comparable to that of the solid metal; a condition necessary for the attainment of useful permeability values.

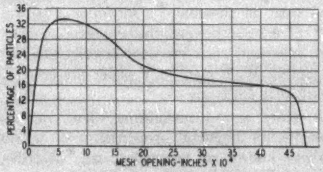

FIG. 3—DISTRIBUTION OF PARTICLE SIZES IN ANNEALED POWDERED PERMALLOY. CURVE SHOWS PROPORTION BY WEIGHT OF PARTICLE SIZES GRADED ACCORDING TO MESH OPENINGS DIFFERING BY 0.001 IN. STEPS

The method employed makes use of several refractory materials, some of which are mixed dry, with the permalloy powder, and others then added in a water solution. The amount of insulating material added is regulated so as to control within limits the permeability of the pressed cores. The mixing is done in a rotating barrel, shown in Fig. 4. This barrel is heated while it

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9. U. S. Patent 1523109, Jan. 13, 1925, G. W. Elmen

revolves, and in the course of mixing the volatile ingredients are evaporated; and finally a brownish, insulated powder is obtained. In the development of methods of insulating the powder, and making cores suitable for loading coils, the work of J. W. Andrews, R. Gillis, and A. F. Bandur, of the Western Electric Co., may be particularly mentioned.

The insulated, permalloy powder is formed into cores by pressing it in steel dies at approximately 200,000 lb. per sq. in. Fig. 5 shows the effect of forming pressure upon permeability. For performing this operation the improved press shown in Fig. 6 has been developed.

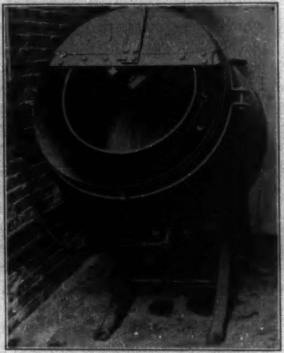
Fig. 4—Drum for Insulating Permalloy Powder

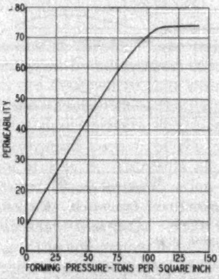

Fig. 5—Effect of Forming Pressure on Permeability of Compressed, Powdered Permalloy

This press is equipped with a pneumatic-cushion base so that, when the pressure builds up to the desired value, it is automatically relieved. On account of this construction the press is more rapid and economical in operation than the steam-hydraulic press mentioned in the Speed-Elmen paper, and gives a more uniform product. The various pressures required by different sizes of cores are attained by the proper setting of a release valve. The press can be calibrated by the use of a Crosby Indicator that records the pressure throughout the whole pressing cycle, as an ordinary gage is not able to follow this fast cyclic change.

It has been mentioned that it is necessary to anneal the compressed powdered permalloy cores. This heat-treating operation also serves to increase the mechanical strength of the pressed cores. It is necessary to control the time and temperature of this anneal rather closely, as annealing at too high a temperature or for too long a time will break down the insulator; and annealing at too low a temperature will not develop the desired low hysteresis loss. This requires that the core parts be brought up to annealing temperature at a rapid rate, and when large charges are annealed the temperature must be uniform. In present commercial practise this annealing is conducted by inserting the core rings in the type of furnace shown in Fig. 7.

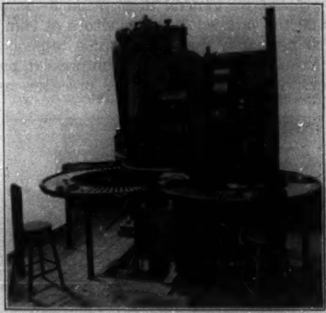
Fig. 6—High-Speed Automatic Release Press

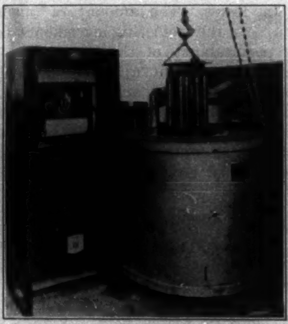
Fig. 7—Annealing Furnace

The heat-treated, compressed powdered permalloy cores contain a small amount of water-soluble matter which is accordingly removed by an extraction process.

After this operation, the cores are vacuum-dried and covered with a thin coating of shellac. The vacuum-drying operation is performed in the same tank that is used for extracting the soluble matter, in order to avoid an extra handling operation. Fig. 8 shows the equipment used for this purpose.

From the above general description it can be seen that while the process of manufacture of compressed, powdered permalloy cores is in some respects similar to the method of manufacture of compressed, powdered iron cores, in many respects the processes are very different. In order to ensure a satisfactory product it is necessary to control closely the manufacturing variables at all stages of the process. The brittleness of the rolled alloy and grain-size of the powder depend upon the melting and hot-rolling conditions that are used, and this grain-size, in turn, has an effect upon the eddy-current losses. The amount of insulator used and the purity of the insulating ingredients also greatly affect the permeability of the core. The hysteresis loss is vitally dependent upon the annealing cycle applied to the formed core parts. The effects of manufacturing variables have, however, been extensively explored. As a consequence, it is possible, by the exercise of careful control, to manufacture a product having well-defined characteristic properties, such as described below.

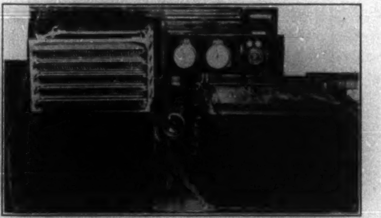

FIG. 8—WASHING AND DRYING TANKS

## PROPERTIES OF COMPRESSED, POWDERED PERMALLOY

*Specific Gravity.* As noted, the relative proportion of powdered alloy and of insulating material is varied in the control of the volume permeability. Within the limits generally found necessary for this purpose, the specific gravity varies from 7.8 to 8.3. These values may be compared with the value of 8.6 for 80-20 Ni-Fe alloy in sheet form.

*Tensile Strength.* As is the case with powdered-iron core rings, the compressed-powdered permalloy rings are quite strong enough to satisfy all manufacturing process requirements, relative to handling and to machine winding. Tests to rupture on individual rings give an average breaking point strength of 265 lb. per sq. in. in tension.

*Resistivity.* The resistivity, as measured by d-c. methods directly on the rings, may vary over a considerable range without having significant effect on the magnetic properties. Typical values are from 1 to 20 ohm-cent. It is found that a resistivity below this range is an indication of incomplete insulation of the particles, and of higher than normal eddy-current losses.

*Permeability.* This property is of prime importance in a material for use in loading-coil cores. The function of the loading coil is to add a specific amount of inductance to the telephone circuit at each of the periodic points at which these coils are inserted serially into the line. In the ideal case, the inductance, so added, would be perfectly constant under all conditions of service, and the coils used for the purpose would introduce no additional losses into the circuit. In practise, of course, these ideal characteristics are only approximately realized. Each coil necessarily adds the d-c. resistance of its windings to that of the circuit. Power losses in the magnetic material of the core contribute an added resistance factor. The constancy of the core permeability under the conditions of normal operation and of service hazards limits the inductance constancy of the coil. At a given cost for the loading, the magnitude of the permeability defines the lowest winding resistance that can be obtained and, likewise, but more indirectly, the core-loss resistance. From the standpoint of obtaining coil windings of low d-c. resistance alone, the permeability should be as large as possible. However, it is a matter of experience, with magnetic materials now available, that high permeabilities are not associated with high degrees of constancy nor with the lowest power losses. Consequently, a compromise giving the best balance between the conflicting factors must be sought. This usually leads to permeabilities of lower value than can be advantageously employed in other types of electrical apparatus. Fig. 9 shows a typical permeability-induction characteristic for both powdered permalloy and for Grade B powdered iron. The significant differences in favor of the new material are (1) its much larger initial value, being over twice the value for the powdered iron (2) the wider

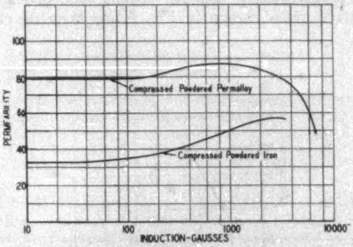

FIG. 9—PERMEABILITY-INDUCTION CHARACTERISTICS OF COMPRESSED POWDERED PERMALLOY AND GRADE B COMPRESSED POWDERED IRON

range of induction over which it is substantially constant, from 0 to 100 gausses as compared with 0 to 30 gausses, (3) the smaller percentage change over a rather wide range of induction. For example, the maximum change from the initial value up to an induction of 4000 gausses is about 10 per cent as compared to 75 per cent for the powdered iron. The values exhibited by these curves are for typical samples. Differences of initial permeability between individual cores must be allowed for commercial manufacture. For the compressed powdered permalloy all cores have values between 69 to 81, allowing a maximum variation from the mean of about ± 8 per cent. Considering the varied nature of the processes through which the material for the cores, and finally the cores themselves, have to pass, in the course of which the permalloy is subjected to severe mechanical working and to large stresses (and the well-known sensitivity of permalloy in these respects), this tolerance is seen to be extremely close. In comparison, it may be noted that in other magnetic materials as ordinarily manufactured, variations of ± 30 per cent in permeability are very common.

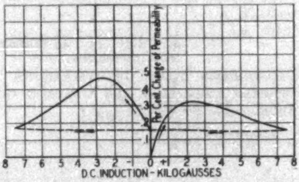

FIG. 10—RESIDUAL EFFECT OF D-C. INDUCTION ON THE INITIAL PERMEABILITY OF COMPRESSED POWDERED PERMALLOY

In the manufacture of the coils their inductances are still further controlled by adjustment of the windings.

Loading coils are designed so that over the normal range of telephone-current values the induction in the coil cores due to these currents does not exceed the initial nearly horizontal portion of the permeability-induction curve of Fig. 9. Currents of much larger value may, however, result from induction or accidental connection to sources of d-c. or low frequency power; and it is a requirement that these service hazards shall not seriously alter the coil inductance. In this respect the portion of the curve at inductions above 600 gausses is of interest. An effect of more importance, however, than that shown by this curve is indicated in Fig. 10, which shows typical changes in initial permeability due to the residual effect of previous large inductions, both positive and negative. It will be noted that the change has a maximum value in the vicinity of an induction of 2500 gausses. The changes are, however, markedly small, the maximum departure from the initial point being less than 0.5 per cent. Having once been heavily magnetized the material acquires a new mean permeability, about 0.2 per cent higher than it had initially; and departures from this value do not normally exceed 0.3 per cent.

Besides remaining constant with respect to the normally transmitted current, as well as to the effects of larger accidental currents, the loading coil must remain quite uniform in inductance over a wide range of frequencies. Voice-frequency circuits, having the highest cut-off frequency used at present for commercial service, require efficient operation up to about 6000 cycles.[10] Variations of inductance with frequency may result from the screening effect of eddy-currents in the core. Hysteresis losses, if large enough, will also cause the inductance (equivalent series value) to vary with frequency. The losses in the powdered permalloy cores are so small, however, that variations from these sources can be entirely neglected over the above range of frequency. In fact it is not until frequencies of the order of 100 kilocycles are reached that these effects begin to be significant.

*Core Losses.* In the application of the material to specific designs it is necessary to know the relation between the core losses, frequency, and value of the operating induction, or flux density. For the purpose of studying these relations the equation:

$$W = \eta\, v\, f\, B^{x} + \gamma\, v\, f^{2}\, B^{2} \qquad (1)$$

is a useful starting point. However, as the matter of final interest is the equivalent series resistance of the coil, it is convenient to reduce the above equation to the following form:

$$\frac{Rt}{L} = 8\,\pi\,\eta\, f\,\mu\, B^{x-2} + 8\,\pi\,\mu\,\gamma\, f^{2}. \qquad (2)$$[11]

The symbols in these equations have the following significance:

$W$ = power loss in ergs per sec.
$\eta$ = hysteresis coefficient.
$v$ = core volume in cm.$^3$
$f$ = frequency in cycles.
$B$ = maximum flux density.
$\gamma$ = eddy-current coefficient.
$Rt$ = equivalent series resistance due to core loss.
$L$ = inductance of coil in henrys.
$\mu$ = permeability
$x$ = hysteresis exponent.

The first terms of the right-hand members of the two equations give, respectively, the hysteresis loss and the equivalent series resistance caused by it, and the second, the eddy-current loss and its equivalent series resistance. Considering the latter it is evident that the effective resistance due to eddy-current losses is independent of the operating induction; that is, a coil of given inductance having a constant permeability core will have the same resistance due to eddy-current loss, regardless of whether it is made small or large. This, especially for the higher frequencies where the eddy-current losses may predominate, is a serious limitation to the design of high-efficiency coils. The factor $8\pi\mu\gamma$ is a constant for the material that defines its quality from the eddy-current loss standpoint. To insure low eddy-current losses, it is necessary to make this factor relatively small. In the case of the powdered permalloy this is accomplished not only by reducing the eddy-current coefficient $\gamma$ by the use of insulated finely ground particles, but also by limiting the working permeability of the compressed core. Table I-*A* lists averages values of eddy-current coefficients and the product $\mu\gamma$ for the powdered permalloy and for grade B powdered iron. The coefficient for the permalloy material is nearly 50 per cent less than that of the powdered iron, in consequence of which the product $\mu\gamma$ is only 38 per cent larger—even though the permeability is more than doubled.

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[10] Shaw-Fondiller. *Loc. cit.*

[11] For the derivation of this equation reference is made to Speed-Elmen, *Loc. cit.*

TABLE I
MAGNETIC PROPERTIES OF COMPRESSED-POWDER CORES AT LOW INDUCTIONS

A. *Permeability and Eddy-Current Coefficient*

| | Permalloy | Grade B iron |
|---|---|---|
| Permeability—$\mu$ (mean) | 75 | 35 |
| Eddy-current coefficient—$\gamma$ | $0.0021 \times 10^{-6}$ | $0.0035 \times 10^{-6}$ |
| Product—$\mu\gamma$ | $0.16 \times 10^{-6}$ | $0.123 \times 10^{-6}$ |

B. *Hysteresis Loss*

| Induction ($B_{max}$) | Loss, ergs per cm.³ per cycle<br>Permalloy | Iron (see note) |
|---|---|---|
| 1 Gauss | $0.017 \times 10^{-4}$ | $0.064 \times 10^{-4}$ |
| 2 " | 0.08 | 0.33 |
| 5 " | 0.64 | 3.5 |
| 10 " | 3.7 | 23.8 |
| 15 " | 10.7 | 75.5 |
| 20 " | 23.5 | 172 |
| 30 " | 72 | |

Note: Hysteresis loss values for the powdered iron are about 8 per cent lower than those given by Speed and Elmen; this reduction being due to a small improvement made in the Grade B material subsequent to the publication of the Speed-Elmen paper.

Table I-*B* gives data showing the hysteresis loss in ergs per cu. cm., per cycle, for a typical range of flux densities. These data are plotted in Fig. 11. On account of the large ratios represented, logarithmic scales are used so as to open up the plot at the lower values. The curves show a slight departure from linearity, indicating that the hysteresis exponent $X$ is not a constant even for the small inductions represented. The curves for the two materials are, however, nearly parallel showing them to have at each point about the same exponent. The outstanding difference is the large displacement between them. For a given hysteresis loss powdered permalloy is capable of operation at much higher densities.

The factor $\eta B^x$ of the hysteresis term of the loss equation evidently is the loss per cubic centimeter, per cycle. Hence, dividing the latter by $B^2$ there is obtained the variable part of the corresponding term of the equivalent resistance equation, that is $\eta B^{x-2}$. Such values multiplied by the mean permeability are plotted in Fig. 12. The ordinates of these curves multiplied by the factor $8\pi f$ give the hysteresis loss resistance in ohms per henry for the frequency and flux density desired. Here the outstanding superiority of the powdered permalloy is more clearly evident, the ratio of resistances due to hysteresis losses mounting very rapidly with increasing density.

These curves show at a glance the density at which hysteresis loss resistances are equal. Of course, it is often more important to have the total core loss resistances equal at a particular frequency. Since the eddy-current resistances are, as previously mentioned, constant with respect to flux density, it follows that their difference is also constant. Hence, a curve drawn parallel to, and displaced from, the hysteresis loss curve along the loss axis to an amount proportional to this

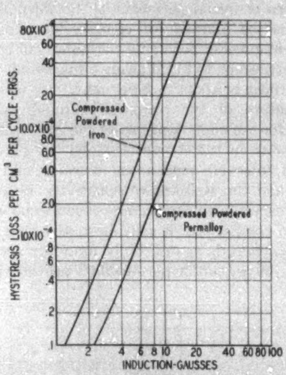

FIG. 11—HYSTERESIS LOSS CHARACTERISTICS OF COMPRESSED POWDERED PERMALLOY AND GRADE B COMPRESSED POWDERED IRON

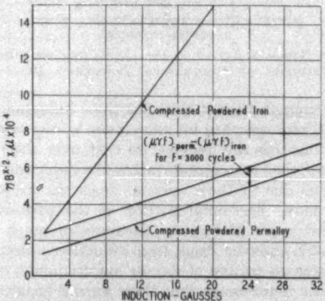

FIG. 12—RELATION BETWEEN A-C. INDUCTION, $B_{max}$, AND HYSTERESIS LOSS RESISTANCE FACTOR, $\eta\ B^{x-2} \times y$, FOR COMPRESSED POWDERED PERMALLOY AND COMPRESSED POWDERED IRON

difference gives the densities at which total core-loss resistances are equal. Such a curve is included in Fig. 12 for a frequency of 3000 cycles, this being slightly above the maximum frequency which certain powdered-iron core loading coils were designed to transmit efficiently.[12]

It is interesting to note here the reduction in core volume that can be effected by the substitution of the powdered permalloy for the previously standard powdered iron, equal or higher efficiency as to core loss resistance being obtained. Assume a toroidal core of uniform cross-sectional area $A$ and of mean circumference $l$, wound with $N$ turns of wire.

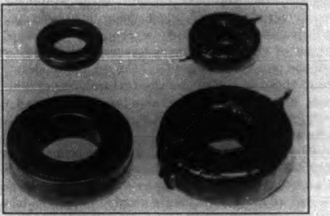

Fig. 13—Right—Compressed, Powdered Permalloy and Compressed, Powdered Iron Core Loading Coils of Equal Efficiencies. Left—Cores Used in these Coils

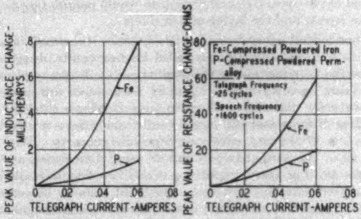

Fig. 14—Relation between Current and Third Harmonic Modulation Product for Coils having Cores of Compressed Powdered Permalloy and Compressed Powdered Iron

$$\text{Since } L = \frac{4\,\pi\,N^2\,A\,\mu}{10\,l},\ N^2 = \frac{10\,l\,L}{4\,\pi\,A\,\mu} \text{ approx.} \qquad (3)$$

$$B = \frac{4\,\pi\,N\,I\,\mu}{10\,l} \qquad (4)$$

$$\text{Combining (3) and (4) } B^2 = \frac{4\,\pi\,\mu\,L\,I^2}{10\,l\,A}$$

$$\text{Substituting } V \text{ for } l\,A,\ B^2 = \frac{4\,\pi\,\mu\,L\,I^2}{10\,V} = \frac{K\ \mu}{V}$$

$$\text{And} \qquad V = \frac{K\ \mu}{B^2}$$

That is, for a given inductance, core volume is proportional to permeability and inversely proportional to the flux density squared.

A largely used toll cable circuit loading coil of the compressed powdered iron core type operates at an average flux density of 5.6 and the cut-off frequency of the circuit is about 3000 cycles. From Fig. 12, the flux density for a permalloy-core coil to have the same core loss resistance at this frequency would be 19; hence the core volume of the latter would be

$$\frac{75}{35} \times \left(\frac{5.6}{19}\right)^2 = 0.187 \text{ times that of the former, a ratio of}$$

about 1 to 5. On the other hand, the lower hysteresis loss characteristics of the permalloy material may, without increase in cost, be utilized to give coils of higher quality not only in respect to effective resistance, but also in respect to their tendency to produce "flutter"[13] when used in circuits having joint telephone and telegraph service, and to introduce inter-channel modulation in multi-frequency carrier telegraph systems. For the initial application of this material to commercial use, an intermediate course is being followed; that is, coils both lower in cost and better in quality in all of these respects have been developed. For the two main types of facility required, core volumes have been decreased by 70 per cent in one case and by 85 per cent in the other. Fig. 13 illustrates the larger of these reductions in core and coil sizes. Combined with these reductions in size, and consequent savings in cost, there are appreciable improvements in effective resistance and also, as noted below, in flutter and modulation.

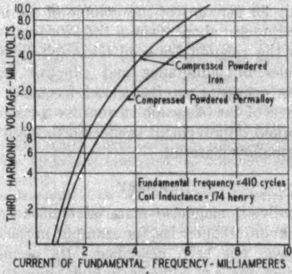

Fig. 15—Telegraph Flutter Effects in Coils Having Cores of Compressed Powdered Permalloy and Compressed Powdered Iron

*Modulation Effects.* Under this heading are included the effects mentioned above as telegraph flutter and also what is more commonly recognized as a modulation effect, namely the production of harmonic electromotive forces by a varying flux of fundamental frequency. As these effects are closely associated with hysteresis characteristics it would be expected, from the general data previously given, that the permalloy material would be decidedly superior to the powdered-iron material. In view of the dependence of hysteresis loss on the working flux density, as shown by Fig. 11, it is clear that the specific results obtained can be controlled by design. For a more definite comparison therefore Fig. 14 is shown, giving the relation between the line current of fundamental frequency and the induced, third harmonic voltage for two standard designs of loading coils, one having a powdered-iron and the other a powdered-permalloy core. A reduction of from 30 to 40 per cent in the third harmonic product is obtained by the use of the permalloy core even though it has only 30 per cent of the volume of the iron core and is operated at about 3 times the flux density. Fig. 15 shows the relation between telegraph current and peak values of inductance and effective resistance increments occurring in the speech-frequency circuit in each cycle of the telegraph current for the same coils. Again marked improvement is effected through the use of the permalloy material.

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[12] See Table X, Shaw-Fondiller, Loc. cit.

[13] *Hysteresis Effects with Varying Superposed Magnetizing Forces*, W. Fondiller and W. H. Martin, Trans. A. I. E. E., Vol. 40, 1921, p. 443.

## SUMMARY

An improved, magnetic material eminently suited for use at audio frequencies, for example, in the cores of loading coils, has been described. Its permeability at low inductions is of sufficiently high value to permit the design of small coils with relatively low-resistance windings, and is constant to a marked degree under all conditions of service. Its eddy-current and hysteresis losses are much smaller than those of any other magnetic material of comparable constancy of permeability. These characteristics have made possible the development of new loading coils for exchange area and toll cable loading of about 1/5 and 1/3 the size respectively of former coils, not only with no sacrifice as to quality but, actually, with very appreciable improvements in transmission efficiency, inductance stability, and modulation.

Despite the high cost of nickel as compared with iron and the relatively large proportion of it used in the permalloy, the reduction in coil sizes results in large savings in manufacturing and installation costs. It would not be possible, of course, to effect these savings were it not for the fact that the net cost of manufacturing the cores is sufficiently low. A method that accomplishes this result has been described. In the development of this method difficult technical problems involved in powdering the permalloy, and in insulating the powder, so that subsequent high-pressure forming and high-temperature heat-treating operations could be applied have been solved. The processes are adaptable to economical, large-scale production and at the same time can be controlled so as to insure a highly uniform product meeting the stringent requirements for a loading-coil core material imposed by recent long-distance telephone circuit developments.

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## Discussion

**F. B. Jewett:** The commercial use of permalloy-dust-core loading coils as successors to iron-dust loading coils, which in turn were improvements over and successors to the earlier types of iron-wire-core coils, has brought about a number of very important improvements which have not been particularly stressed in the paper, which is primarily concerned with a description of the manufacturing features and physical characteristics of the new core material. I should like to draw attention to two of these important service features, one of which affects the local distributing plant in our larger cities, and the other our very long loaded cables such as those connecting New York, Chicago, and St. Louis.

In the local distributing plant, one of the principal advantages of permalloy-dust loading coils is in their very small size, which permits much smaller cases to be used for potting a given number of coils and allows a much larger number of coils to be potted in the largest cases, thus resulting in a great conservation of space in the underground loading vaults. It is a formidable job to tear up city streets and to put in new structures. A large part of the underground construction in a city like New York is more or less permanently placed. There is a duct system, which was placed in past years, to amplify which would require the opening of the streets and the laying of new ducts.

Since loaded cables are used in our cities, there are, in addition to the ducts, man-holes, called loading vaults, designed to house the pots containing the loading coils. In many places, a few years ago, we were potentially confronted with an early necessity for materially enlarging these housings, either by the building of more and still larger vaults under the city streets or by going off the city streets onto private property. With the coming of the permalloy coil and its small dimensions, and the smaller potting space required per coil, we find it possible to place a considerably greater quantity of coils in the existing structures, and so not only obviate the cost of making changes but also the great inconvenience to street traffic. In the large metropolitan areas, therefore, with their great congestion of circuits, running up to tens of thousands or more along the main routes, we have an advantage which is even more important than the cost saving of the coils themselves.

The other feature which concerns long-distance service is interesting because it is part of a progressive change in the type of line which we use.

In the early days, the telephone plant was on the single-wire, ground-return basis. That had to be abandoned in favor of the all-metallic or two-wire circuit, partly for telephone reasons and partly because of inductive interference troubles which followed the great growth of power and light circuits. For many years our whole telephone engineering was based on the assumption of a two-wire form of communication line. With the coming of amplifying devices, the so-called telephone repeaters, and the extension of these long circuits to very great distances, there was introduced a form of line known as the four-wire circuit. We had gone from one to two wires, for a circuit, and we were proposing to go from two to four, in which one pair of wires served to carry, say, the west-bound conversation, and the other pair the east-bound conversation.

It is not the time and place here to go into the technical discussion of why that was the desirable thing to do, beyond the statement that it resulted in a more flexible and more efficient plant to separate the ordinary two-wire local circuit at one end into a four-wire toll circuit, and at the distant end to recombine it again into a two-wire circuit. This made possible the use in each of the four-wire circuits of one-way repeaters having a very high amplification. With the four-wire circuit, roughly speaking, the same amount of copper for a given distance is involved in a telephone cable as with the two-wire circuit. For instance, over a given distance with a two-wire circuit we use 16-gage copper, while on the four-wire circuit we use 19-gage copper wire—exactly the same amount but drawn into four instead of two wires. Since, with cable, the cost is largely made up of material values, the copper and paper and the lead encasing sheath, the inherent cost of the four-wire against the two-wire circuit is nearly the same, but when you begin to add loading coils on these very long circuits you are adding something to the material cost of the cable itself, which is not an inconsiderable part of the total cost. So with the higher priced loading coils, despite the other advantages of the four-wire circuit, there was a tendency to restrict its use to conserve cost, because of the loading coils themselves. But with the introduction of the permalloy-dust-core coils, which are not only much smaller but considerably cheaper, there is introduced a factor which makes it possible for us on long telephone cable circuits to go further in using the four-wire type of structure.

**Bancroft Gherardi:** In round figures, today, we have in our plant 3,000,000 loading coils. That is to say, for every 6 telephone instruments connected with the Bell System, there is one loading coil, and we are adding to that number at the rate of about 700,000 a year, the same rate with which we are adding telephone stations connected with the system. So it is evident that the loading coil, not only in the results which it produces but in the numbers used, is a factor of major importance in our plant.

**B. A. Behrend:** It will be interesting to recall the first suggestion of the use of powdered iron for increasing the inductance of a telephone or telegraph circuit without materially increasing the resistance. In his "Electrical Papers," vol. II, p. 123, 1902, Oliver Heaviside makes this statement: "One way is with my non-conducting iron . . . . . an insulator impregnated with plenty of iron dust." Further references occur on p. 275 in the same work where Heaviside states that he "rolls the resulting compound, when in a slightly yielding state, under considerable pressure, into the form of solid round cylinders." In "Electromagnetic Theory" vol. I, p. 443, he suggests again "loading the dielectric itself with finely-divided iron" and he calls this his "ironic" circuit. This reference occurs within a page of the famous suggestion of using "inductance in isolated lumps" for loading cables or circuits though there appears no suggestion that the cores of these loading coils should be made of this powdered iron. With the increasing appreciation of the theoretical work of Heaviside's this historical reference may be of interest.

**Wm. Fondiller:** There are one or two points that are mentioned in the paper that I want to emphasize, because I think that they are rather important.

First is the matter of the higher permeability of the powdered-permalloy cores as compared with the powdered-iron cores. You can get high permeability, by suitable heat treatment of any magnetic material, but unless at the same time you can keep down the losses in the case of loading coils that increase in permeability is of no avail. The fact that it has been possible with powdered permalloy to more than double the permeability that was available with powdered iron, marks a really important accomplishment, particularly when it is coupled with extremely high magnetic stability. The magnetic stability is evidenced by the fact that up to an induction of $B = 100$, the permeability is almost absolutely constant, a performance not attained with any other magnetic material. It is particularly striking in view of the seemingly anomalous fact that in sheet permalloy you get enormous changes in reduction with small changes in value of $H$. The flat characteristic of the powdered-permalloy cores is due to the beneficent effect of numerous air gaps introduced by the core design.

It is also significant that with a core with 80 per cent nickel in it, a material which costs over ten times that of iron, in ingot form, it has been possible to produce loading coils having better properties at a lower cost, by virtue of a great reduction in the amount of core material and copper windings.

I want to mention one other thing of interest. The powdered permalloy core has practically the composition, that is, between 80 and 81 per cent nickel, that was pointed out by Dr. McKeehan to be the alloy which would have zero magneto striction. To this fact Dr. McKeehan attributed the extremely low hysteresis loss of permalloy.

**Eugene Herzog:** Can this same type of material be extended to uses in other electrical apparatus? I see from Fig. 9 that the permeability of this material has an induction of about 2000 and from there drops off very rapidly, and as in most power apparatus a much higher induction is used, I should like to ask the authors whether they have made any attempt to develop a material which could be used successfully at a higher induction.

**W. J. Shackelton:** In response to the last question, I will say that we have not made any particular attempt as yet to apply this material to other fields than the telephone field. The fact that its permeability over a wide range of induction is low as compared to the values ordinarily used in power apparatus would lead me to believe that its chance for application in this field would be rather small. Where its permeability is not a limitation, however, it can be used even at fairly high inductions.

# The Effect of Humidity on the Dry Flashover Potential of Pin-Type Insulators

BY J. T. LITTLETON, JR.* and W. W. SHAVER*
Associate, A. I. E. E. Non-member

**Synopsis.**—*This paper shows that humidity affects considerably the flashover voltages of porcelain and Pyrex insulators. The flashover potential rises as the humidity is increased. The tests were made on pin-type insulators and on rods. The results show that this rising characteristic is a surface effect which varies with the absolute water content of the surrounding atmosphere.*

## INTRODUCTION

IT is probably generally recognized that the humidity or water content of the atmosphere has some effect on the flashover potential of insulators. The A. I. E. E. specifications for testing insulators[1] state that relative humidity measurements should be taken at the time of the test and recorded as part of the data. No correction factor for this condition has been worked out, however, and little seems to be known as to the quantitative effect of humidity changes. It seems to be a general belief that an increase in humidity leads to a decrease in flashover. Peek[2] has stated that humidity does not affect the flashover potential of sphere-gaps. Schwaiger[3] has given data on porcelain and glass rods in uniform tangential fields, showing a lowering of flashover potential with increase of humidity, and curves showing an increase in flashover potential on large insulators and constant flashover potential on small insulators with increase of humidity. Accordingly, it seemed worth while to determine the quantitative relationship between humidity and flashover potential on different types of insulators and insulators made of different materials, and, if possible, to work out a correction for this condition.

While the work on this problem has not been completed, inasmuch as no correction factor has been completed, it is believed that the measurements obtained are of sufficient value and interest to justify their presentation.

## EXPERIMENTS

The electrical equipment consisted of a 150-kv-a., center-grounded, 60-cycle transformer with maximum voltage of 300 kv.. controlled by an induction regulator. Flashover voltages were measured in either of two ways; (1) by a voltmeter previously calibrated with a sphere-gap, or (2), directly by the sphere-gap in parallel with the insulator with suitable high resistances on each side of the gap to prevent errors due to oscillations from the insulator under test.

The insulators were mounted and the tests conducted as nearly as possible according to the A. I. E. E. specifications for testing insulators.[4] The tests were made in a wooden box 6 ft. square and 5 ft. high with a hinged cover, all lined with waterproof paper. These dimensions gave less than the standard clearance for the insulator mounting so that in this respect the tests were not made according to the standard specifications. This condition did not noticeably affect the results, as measurements made in the box agreed with those taken in the room for comparison. The iron pipe holding the insulator pin ran diagonally through the box and projected through the walls so that the one lead was connected to it on the outside. The other lead to the half-inch brass rod tied in the line groove was insulated from the chamber wall by a large bell shaped pyrex insulator.

FIG. 1—PYREX INSULATORS USED IN TESTS

FIG. 2—PORCELAIN INSULATORS TESTED

The humidity in the test chamber was controlled by the introduction of dry steam circulated throughout the box by a fan. Because of small leaks it was found necessary to introduce steam continuously in order to maintain a given humidity. Humidity measurements were made by means of a dry and wet bulb hygrometer suspended in the current of air from the fan, just inside a window through which the readings were taken. These results were converted to absolute humidity by means of the data given in the Psychrometric and Smithsonian tables.[5]

The experimental procedure was as follows; the insulator was mounted on the pin in the test chamber

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*Both with the Corning Glass Works, Corning, N. Y.

[1] For all references see bibliography.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Feb. 13-17, 1928.*

and a standard dry flashover test made with the natural humidity of the atmosphere. Steam was then introduced in the chamber and the humidity thereby increased and maintained at a constant value for 15 min. A second flashover test was then made and the cycle repeated. If it were desired to decrease the humidity after it had reached a point near saturation the cover of the box was raised and fresh air admitted. So far as possible, a given series of tests was made at a constant temperature, but on account of the steam used in the test, the temperature slowly increased, in an extreme case changing by as much as 4.5 deg. cent. However, temperature and pressure as well as relative humidity were recorded for each test and a correction applied to reduce the values to those for 25 deg. cent. and 760-mm. pressure.[6]

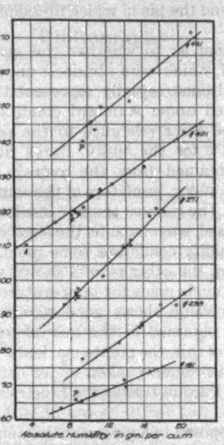

FIG. 3—VARIATION OF FLASHOVER POTENTIAL WITH HUMIDITY, ON PYREX INSULATORS

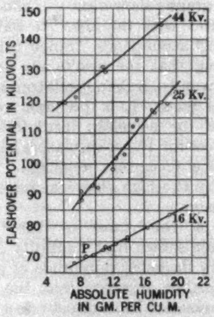

FIG. 4—VARIATION OF FLASHOVER POTENTIAL WITH HUMIDITY, ON PORCELAIN INSULATORS

Measurements were made upon different types of Pyrex pin-type insulators (see Fig. 1) and upon porcelain pin-type insulators, (Fig. 2), varying from 16- to 44-kv. rating. Tests were also made on the effect of humidity on the flashover potentials between No. 6 copper wire electrodes wrapped around Pyrex rods of various diameters, and at various spacings. In addition, in order to determine whether or not the phenomenon was merely due to the humidity effect on the electrodes, measurements were made on the flashover potentials between a one-inch steel bar bent in the shape of a hook, and a loop of No. 8 copper wire, as well as between two loops of No. 6 copper wire.

## RESULTS

Figs. 3 and 4 show the results of a series of tests on the different Pyrex insulators and porcelain insulators, respectively. In every case there was a marked increase in the flashover potential when the humidity was increased. These curves do not show the maximum variations that have been observed, as considerably greater variations are possible when the experiments are made at a higher temperature, the maximum possible water vapor content in that case being much greater. In general it was found possible to increase the flashover potential of both Pyrex insulators and porcelain insulators about 30 per cent over the value at a low humidity.

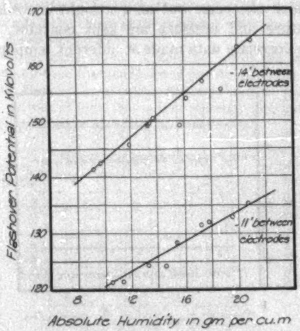

FIG. 5—VARIATION OF FLASHOVER POTENTIAL WITH HUMIDITY, ON PYREX ROD, 0.9 IN. IN DIAMETER

The results of some of the experiments on Pyrex rods are shown graphically in Fig. 5 and again, increased humidity caused increased flashover potential. The results shown were obtained with a rod 0.9 in. in diameter and with the spacings between the electrodes as indicated on the graphs.

Fig. 6 shows the results of the measurements on the flashover potentials between the loop of No. 8 copper wire and the one-inch steel rod bent in the form of a hook and between the two loops of No. 6 wire. In the first case, they were spaced so as to give a flashover potential about the same as that of a 44-kv. insulator; and in the case of the loops of No. 6 wire, the spacing was the same as when they were wrapped around a pyrex rod. From the slopes of these curves, it is quite evident that the humidity effect on the flashover potential of an insulator and of a Pyrex rod cannot be attributed to any effect on the electrodes.

## DISCUSSION AND CONCLUSIONS

As mentioned above, the curves show humidity values expressed in absolute units, since such units bring the measurements taken under different temperature and pressure conditions more nearly in agreement with each other than do those of relative humidity. Schwaiger[7] shows data plotted on a relative humidity basis which also come out as a straight line relation if temperature and pressure are kept constant, but in order to correlate data made at different temperatures, or to work out a correction factor, it is necessary to use absolute humidities. In addition he shows that in the neighborhood of 100 per cent relative humidity the flashover potential falls very rapidly, this effect beginning at even 80 per cent humidity on certain insulators. This decrease in flashover potential was noted in our experiments at humidities above 90 per cent, but it is believed that this was due to condensation on the insulator surface, which could be avoided by having the insulator at the proper temperature. Schwaiger's results indicate no humidity effect on flashover potential with an insulator of approximately the same dry flashover potential as the Pyrex insulator No. 161 and the 16-kv. porcelain insulator. Our observations made on the latter insulators indicate a very definite effect and one which is also of considerable magnitude. Weicher[8] investigated the effect of humidity on the flashover potential between points and 2-cm. spheres so spaced as to give a flashover potential approximately the same as indicated in Fig. 6, and found that the flashover potential increased with increasing relative humidity. This does not agree with our observations on the flashover potentials between the two loops of copper wire and between the copper wire and the pin in which no humidity effect was observed.

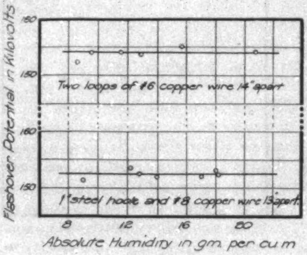

FIG. 6—FLASHOVER POTENTIAL BETWEEN METAL WIRES AND BETWEEN HOOK AND WIRE

Above, two loops of No. 6 copper wire, 14 in. apart.
Below, a 1-in. steel loop and a No. 8 copper wire, 13 in. apart

The question as to whether the curves shown in Figs. 3 and 4, which were obtained under more or less artificial conditions, actually represent the phenomena when observed under standard conditions, is perhaps best answered by a reference to the point *A* on the curve in Fig. 3 for the 40-kv. Pyrex insulator. This point was obtained from the average dry flashover values of five 40-kv. insulators of the same type as used in this test. The tests on the five insulators were made in the standard way outside the test box under low, absolute humidity conditions some months previous to the time when the other results shown were obtained. When correction is made for temperature and pressure, however, this value shows good agreement with the other results obtained in the special test box. As a further proof of this, the points marked *P* on the curves represent measurements taken under natural humidity conditions at Purdue University Electrical Engineering Laboratory.

It is not proposed to advance at this time any theoretical explanation of the results obtained, as the data at hand are not sufficient to warrant the development of any very definite theory. The results given on the accompanying graphs show that the effect is a surface one which varies with the absolute water content of the surrounding atmosphere. Since this is true, it is not surprising that the results are similar for both Pyrex insulators and porcelain insulators, as in both cases the surface is of glass. It is perhaps worthy of note that the slopes for porcelain insulators are slightly steeper than those for Pyrex insulators having approximately the same flashover potential. This may be accounted for by the high chemical resistivity surface of Pyrex insulators.

Regardless of the cause of the phenomenon, experiments have shown that humidity has a marked effect on the dry flashover potentials of pin-type insulators. It is further apparent that the large change occasioned by humidity has a direct effect on the rating of an insulator. Extrapolation from the curve, together with temperature and pressure corrections, shows that a No. 441 Pyrex insulator at 760-mm. pressure and 35 deg. cent. temperature would flash over at 128 kv. with a 10 per cent relative humidity and at 193 kv. with a 90 per cent relative humidity.

Moreover, the apparent straight line relation between flashover potential and absolute humidity makes it possible to adopt a correction factor for the humidity effect on a given insulator, and to catalogue the dry flashover potential at a standard humidity as well as at a standard temperature and pressure. Until a satisfactory theoretical correction factor or formula has been determined so that humidity corrections can thereby be made it is believed that curves such as those given should be used as a measure of the standard dry flashover value of an insulator rather than a measurement at one known humidity.

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4. Loc. cit.

5. Psychrometric Tables by C. F. Marvin, U. S. Dept. of Agriculture. Smithsonian Tables, 1927 edition, p. 185.

6. Peek, loc. cit., page 111. The maximum possible correction as given by the formula $\frac{3.92 \times \text{Bar. pressure in cm.}}{\text{Absolute temperature}}$ was used in all cases.

7. Loc. cit

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## Discussion

**W. L. Lloyd, Jr.:** (by letter) It has long been recognized that humidity has an effect upon the sparkover voltage of certain gaps and insulating members. The effect varies with the type of gap or the type of insulator or bushing. The effect of humidity on the needle-gap was shown in a paper before the A. I. E. E. by F. W. Peek, Jr.[1] The spark-over voltage increases with the humidity. The sphere-gap on the other hand is apparently not affected by humidity; at least in the papers referred to above, tests indicated that the effect, if any, is within the ordinary limits of accuracy for the sphere-gap so that no connection is possible.

For an insulator or bushing of the usual design an increase in humidity causes an increase in sparkover voltage. The effect, however, is ordinarily not of sufficient magnitude to be a factor in the insulation of a line or the number of flashovers on the line. The variations due to humidity are small compared with the difference between the flashover voltage and the operating voltage. Moreover, where the laboratory tests are made in a room that is not too damp, the variation from the laboratory test results will be in the direction of safety, *i. e.*, towards a higher sparkover voltage. In tests, to meet specifications, however, where the guaranteed sparkover is close to the actual sparkover of the insulator or bushing a few kv. may be a matter of acceptance or rejection of the product The effect of humidity then becomes of importance and it is necessary to know the humidity correction to be made.

I agree with the statement made on the third page of the paper in that the correction curves are similar "for both Pyrex insulators and porcelain insulators as the surface is a glass in both cases," but I am perplexed at the next two sentences. I have plotted the data given in Fig. 3 for porcelain on top of the data given in Fig. 2 for Pyrex and I cannot notice any difference in the average slope of these curves. If any difference in the slopes were to be found I would attribute the difference to a difference in the design of the insulators rather than to a difference in the materials or the chemical properties of the materials since it is a fact, and a fact admitted by the authors, that the surface in both cases is a glass.

**E. D. Eby:** This subject of the effect of humidity upon the arc-over potential of insulators, and bushings, and gaps, is one of great importance to us from the standpoint of testing, because the variations encountered are such as to require a correction factor. And it seems strange that up to this time no serious attempt, apparently, has been made to collect sufficient data from which could be derived a correction factor which could be used for different classes of insulators. We need such correction factor to harmonize the results of our tests, and also to provide a basis for the rating of insulators and bushings. As the authors have pointed out, the great variation in the arc-over potential is something which immediately affects the rating of the insulator.

It isn't so important that this matter should be investigated from the standpoint of operation of the insulators, because the 60-cycle tests over the range of humidities which have been observed, do not seem to fall below the wet flashover of the insulator; that is, these so-called dry tests at different humidities are always above the wet-flashover value. Since the wet-flashover value is determined according to the rating of the insulator, the variation in dry-flashover voltage due to humidity would not affect the choice of the insulator when that choice is made by the wet-flashover value.

On the other hand, humidity does not affect the operation of the insulator from the standpoint of impulse potential because the impulse flashover is essentially the same whether the insulator is dry or wet; at least that is true generally, not only of so-called insulators but of apparatus bushings as well.

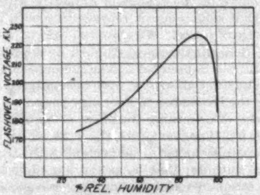

FIG. 1—VARIATION OF DRY FLASHOVER VOLTAGE OF HIGH VOLTAGE BUSHING WITH CHANGES IN RELATIVE HUMIDITY

We have long been aware that different gaps were affected differently by relative humidity in the atmosphere, and probably each different design of insulator, bushing, or gap has a characteristic of its own; but also those designs which are similar in nature probably could have assigned to them a correction factor which would be approximately correct for the group. And so it would be a practical thing to classify insulators and bushings and gaps, and assign to each class some correction factor which would be approximate for the group but nevertheless practical.

Our observations in the past of the great variations in the flashover voltages of apparatus bushings, led us about two years ago to make some tests on apparatus bushings to discover what the effect of humidity might be. We built a box, similar to that of the authors, in which we were able to control the humidity. We did not, however, convert our results into absolute humidity but interpreted them in terms of relative humidity. We varied the relative humidity approximately from 40 to 100 per cent, and with a given design of bushing we found that in that range of relative humidity its flashover potential varied from 180 kv. at 40 per cent to 225 kv. maximum. We noticed that the maximum, in this series of tests, occurred between 90 and 95 per cent relative humidity.

Fig. 1 herewith shows the shape of that curve, which is somewhat more complete than that given by the authors in their paper. These tests were made on a number of different units, and were later confirmed by a large amount of data collected over the succeeding two years on specimen units which have been tested almost every day. This has been done not only at Pittsfield, but also at our Philadelphia works, and the two sets of data are remarkably in agreement. In fact they vary but little from each other.

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[1] See also F. W. Peek, Jr., *Dielectric Phenomena in High Voltage Engineering*, pp. 87-88, Fig. 93.

We found over this period of time that the range of relative humidities encountered in our testing departments at these two plants varied from about 30 per cent to 70 per cent, corresponding to the left-hand portion of the curve in Fig. 1, which is not quite a straight line, but without the rest of the curve might easily have been thought to be a straight line. We found also in this range of humidities that the variation of voltage was about ± 9 per cent from the average, taking the average at 50 per cent humidity, which was the average of the humidities encountered.

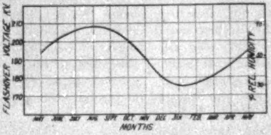

Fig. 2—Seasonal Variation of Relative Humidity and Flashover Voltage of High-Voltage Bushings

We found also a very interesting seasonal change in flashover voltage of these specimen units, following almost identically the shape of the curve of the change of humidity with the seasons. Fig. 2 herewith is such a curve, representing both humidity and flashover voltage of units. We observed that both the humidity and flashover were maximum in August, or approximately that season, from July to September. The minimum humidities, and likewise the minimum arc-overs, were encountered in the month of January, or the December to February period.

**F. M. Clark:** Concerning the effect of humidity on the arc-over values for pin-type insulators, the work which we have done in Pittsfield appears to be in agreement with the results described by the authors; that is, as the humidity increases—we speak of it in terms of relative humidity—we get an increase in arc-over value. In the case which I have at hand this increase amounts to about 20 per cent, a maximum arc-over value being obtained with about 90 per cent relative humidity.

I should like to offer a possible explanation of the phenomena involved. This the authors have avoided. In *La Verre* for 1924, page 54, P. Woog described experiments which he had carried out having for their purpose the detection of changes which occur under certain definite conditions in the surface of glass. Woog set up an apparatus which might be roughly described as a spherical electrode mounted inside of a cylindrical glass vessel which, in turn, was placed on a metallic conductor. The cylindrical glass vessel was filled with oil. When the voltage was slowly increased a discharge was finally obtained from the spherical electrode through the oil to the surface of the cylindrical glass vessel and over this surface to the outside plate electrode.

Working at 25 cycles, with dry oil, Woog found that as the temperature passed from 11 deg. cent. to 100 deg. cent. the voltage to discharge dropped from 67 to 54 kv. There is nothing in the way of experimental error to explain the result.

Using wet oil Woog found that as the temperature was changed from 18 to 12 deg. cent. the arc-over voltage dropped from 65 to 27 kv. approximately. As the temperature was brought back from 12 to 18 and 20 deg. cent. the arc-over voltage again increased to about its original value. In other words, speaking entirely of wet oil, as the temperature increased the arc-over voltage rose.

The author's explanation was somewhat as follows: On the surface of the glass were silicates which were hydrolyzed to give bases with the final formation of a film of sodium carbonate. This material can exist with water of hydration. As the humidity increases this hydration increases until a maximum value is obtained where the ratio between carbonate to water molecules is 1 to 10. What happened, therefore, in Woog's experiments, according to his own explanation, was that the voltage to flashover varied as the author increased or decreased the amount of water in the sodium-carbonate film on the glass. The important thing is that he found that with 10 molecules of water, we will say, in the sodium carbonate, the arc-over value dropped as compared to what it was with the sodium carbonate in the dry state. The effect of temperature tends to increase the arc-over value of moist oil because the decahydrate of sodium carbonate which is formed at low temperature possesses a greater vapor pressure than that characteristic of moist oil with the result that sodium carbonate in a lower stage of hydration is formed.

The present authors have found, as illustrated in Fig. 5, that as the humidity rises the arc-over characteristics also increase. As I have stated, this result is in agreement with the work in our laboratory but it is in direct contradiction to the idea that Mr. Woog has expressed. As Mr. Peek has already demonstrated, and as illustrated in Fig. 6, the dielectric strength of air is not involved. The authors have therefore concluded that the increase in arc-over value with humidity is a surface effect. This they have demonstrated by taking a glass rod and wrapping electrode wires around it, taking the arc-over values between carefully spaced wires. We have often made creepage tests in our work at Pittsfield on all sorts of materials and we find that if we place electrodes as noted by the authors we get an arc-over which is not strictly accounted for by the surface condition of the insulation. Rather we get a result which depends upon the ratio distribution of stress between the insulating surface and the medium in which it is immersed. We have found that we must use some method of holding the voltage stress down into the surface which we are testing. I would suggest to the authors that they accomplish this effect by taking a glass rod, drilling out one end, and filling the well so formed with mercury. They should then wrap a wire around the glass rod directly over the bottom of the mercury well and spaced a definite distance away from a similar wire electrode wrapped about the glass away from the mercury well. The mercury well and its superimposed wire electrode are connected electrically and the arc-over value is taken in the usual manner. With this method the authors may find that they will obtain an arc-over value which is in agreement with the carefully obtained research results described by Woog.

**C. F. Harding:** In view of the fact that the authors of this paper have quoted some of the test values that are closely associated with the curves shown in the paper, these tests having been made in the high-voltage testing laboratory at Purdue University, it may be of interest to have these confirmed in slightly greater detail.

These tests were made upon a wide variety of sizes, not only of Pyrex insulators but also of several makes of porcelain insulators of the pin type, covering the same voltage range.

RESULTS OF SIXTY-CYCLE DRY-FLASHOVER TESTS ON PIN-TYPE INSULATORS WITH VARYING HUMIDITY
PYREX GLASS INSULATORS

(Average of three readings upon each of three insulators of six different sizes)

| Insulator No. | Humidity per cent | Flashover voltage kv. | Humidity per cent | Flashover voltage kv. | Increase humidity per cent | Increase flashover voltage per cent |
|---|---|---|---|---|---|---|
| 1 | 48 | 140.0 | 59 | 161.1 | 23 | 15 |
| 2 | 40 | 137.0 | 60 | 152.0 | 50 | 11 |
| 3 | 43 | 95.4 | 61 | 101.0 | 42 | 6.3 |
| 4 | 40 | 65.2 | 59 | 66.8 | 48 | 2.4 |
| 5 | 40 | 50.0 | 59 | 51.5 | 48 | 3.0 |
| 6 | 40 | 51.3 | 59 | 51.8 | 48 | 1.0 |

PORCELAIN INSULATORS

(Average of three readings upon each of three insulators of ten different sizes of two different manufacturers)

| | | | | | | |
|---|---|---|---|---|---|---|
| 7 | 46 | 152 | 62 | 165.3 | 34.8 | 8.8 |
| 8 | 46 | 127 | 61.6 | 145 | 34 | 14.2 |
| 9 | 48.3 | 119 | 61 | 133 | 27 | 11.7 |
| 10 | 43 | 105.5 | 60 | 125 | 39.5 | 19.4 |
| 11 | 43 | 105 | 60 | 127 | 39.5 | 21 |
| 12 | 43.3 | 91.2 | 63 | 93.1 | 45.5 | 2.1 |
| 13 | 42 | 69 | 59 | 70.3 | 40.5 | 1.9 |
| 14 | 43 | 68.7 | 58 | 70.0 | 35.0 | 1.9 |
| 15 | 40 | 63.6 | 59 | 65.4 | 47.5 | 2.8 |
| 16 | 40 | 48.7 | 59 | 49.6 | 47.5 | 1.9 |

In general, the average of 3 readings under A. I. E. E. 60-cycle standard testing conditions, on three samples of large types of insulators would increase about 15 per cent in flashover, with approximately 23 per cent increase in humidity, that is, from the neighborhood of 40 or 45 per cent to 60 or 65 per cent humidity. This was also true within a smaller range with a similar voltage gradient for the porcelain insulators. With the lower voltage insulators, the per cent increase, of course, was naturally less.

In addition to what has been said about standard or uniform specifications, it would seem desirable to have these A. I. E. E. specifications include the humidity correction, or some humidity measurement plus a correction. If we are to depend at all upon the dry flashover test at 60 cycles, and the Institute has standardized such a test, and if in normal laboratory testing such humidity variations exist, we certainly should have a humidity correction.

Similar tests with steep wave fronts are now being made, in which it is probable that such variations will not exist because, as has been pointed out in the paper and in the discussion, the change in humidity does not affect the sphere-gap and the steep-wave-front measurements in air. So we have the condition that we are testing insulators at 60 cycles, referring our dry-flashover voltages to a sphere-gap which does not change with humidity changes, and yet, from one laboratory to another, unless we do hold humidity constant, we have a 14 to 15 per cent variation in the dry-flashover voltage of such insulators.

**D. H. Rowland:** (by letter) No pains should be spared in studying these phenomena until sufficient data are obtained so that some means may be devised for intelligently taking account of humidity in the A. I. E. E. specifications for testing insulators.

As the authors state it has for a long time been known that humidity affects insulator flashovers. R. H. Marvin pointed this out some years ago.

It has been found in our laboratory that two porcelain insulators having exactly the same flashover values at a certain definite absolute humidity but differing somewhat in corona point, are affected entirely differently by a change in humidity. Thus the curves of flashover against moisture content of the air for two such specimens would not have the same slopes. It is believed, therefore, that the shape of the pieces rather than "chemical resistivity" of the surface is the factor that accounts for the variation of flashover value with humidity for any given insulator. Certainly the curves in the paper under discussion are not definite enough to draw conclusions as to the effects of the surface of the materials under consideration, *i. e.*, glass and porcelain.

Suppose for the sake of argument that there were specimens made up of glass and porcelain of identical shapes for test purposes, there would still be an inherent difference in the dielectric constants of the materials which would affect the electrostatic field and the initial corona point, and as pointed out in the case of the two porcelain insulators, this factor seems to have a bearing on the situation. It would be very difficult to study the surface conditions alone.

Several investigators have found changes in the flashover values obtained between needles with varying humidities. If these data are true it points to the fact that the conditions observed by Dr. Littleton and Mr. Shaver are not as they maintain, entirely a surface effect. More work should be done in this connection.

**W. A. Lewis:** (communicated after adjournment) One characteristic of the experimental conditions, which appears to have an important bearing on the effects obtained, is the form of the electric field surrounding the conductors. As an example, we may compare the results obtained on glass rods by the authors of the paper and by Schwaiger, those of the latter appearing to be checked by our own investigations. The author found that flashover voltage increased with increasing humidity when loops of wire were used as electrodes, whereas Schwaiger found the opposite effect when the glass rods were placed between parallel plate electrodes. The essential difference appears to be in the form of the field, as in the first case the field is non-uniform, the gradient being very high near the electrodes, and in the second case the field is uniform and the gradient constant along the surface of the insulators. Consequently, in the first case initial breakdown occurs near the electrodes and corona forms, but in the other case initial air breakdown and complete flashover are simultaneous.

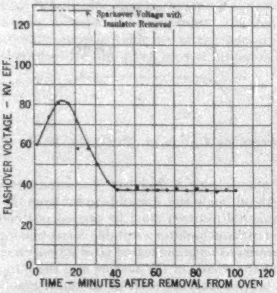

Fig. 3—Flashover Characteristic of Dried Glass Rod, Diameter 214 Cm., Length 7.62 Cm., Air Temperature 21 Deg Cent., Air Density 0.985, Relative to 76 Cm. and 25 Deg. Cent.

Peek has shown that the sparkover voltage of needle gaps, with which marked corona is present, increases with increasing humidity( Diel. Phen., p. 88), and so it does not seem unreasonable for the same phenomena to appear here, when the corona formation is sufficient. The data obtained from flashover between the two wire loops without glass present are insufficient to determine whether this phenomenon is actually present or not, since the field form is considerably altered by the introduction of the glass.

If there is present another phenomenon, independent of corona, which tends to decrease flashover with increasing humidity, it is readily seen that flashover voltage may increase, decrease, or remain constant with increasing humidity, depending upon the relative magnitudes of the two opposite effects. In this way the divergent experimental results may be reconciled.

During the past year experiments have been conducted at the California Institute of Technology, using cylinders of glass between parallel plates. As no test chamber was available in which the humidity could be varied, the expedient was adopted of drying the cylinders in an oven at 90 deg. cent. for several days, and then testing in the plate gap under natural humidity conditions. Flashover voltage was plotted as a function of time, and curves obtained, of which Fig. 3 herewith is a good example.

All curves exhibited the property of starting at a low value, rising to a maximum and falling again to a constant value. The time required to reach the constant value was in no case less than 30 min., which suggests that great care should be exercised to make certain of equilibrium before taking readings, when the controlled humidity method is used.

We explained the shape of the curves in the following way. The low initial flashover voltage was due to the presence of a film of heated air around the insulator, and the flashover voltage rose as the air cooled. At the same time the surface was collecting moisture from the atmosphere, tending to reduce the flashover voltage. When the latter effect overbalanced the former, the curves began to fall and continued until equilibrium was reached. If this explanation is correct, our results would certainly seem to check Schwaiger's, since the flashover voltage decreases with increasing surface moisture, corresponding to increased humidity. The range of atmospheric humidity was insufficient to obtain reliable data by comparison of the equilibrium values of various curves.

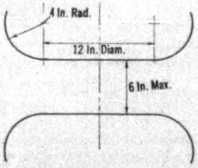

Fig. 4—Section of Circular, Parallel Plate Electrodes

Although a knowledge of flashover characteristics of practical insulators is the ultimate aim, it would appear from the above that much fundamental research must be carried out before we can reach a sound rational basis for a suitable correction factor.

**R. W. Sorensen:** (communicated after adjournment) It will be noted that the results of the authors and those found by Mr. Lewis each taken alone are such as to cause exactly opposite conclusions. That is, the authors of the paper under discussion tell us that for their particular test condition flashover voltage increases with increase in humidity. On the other hand, the results presented by Mr. Lewis indicate beyond doubt that the flashover voltage for the glass rods he used in test becomes lower as the surface of the rod becomes moist. In both cases the flashover is an air breakdown.

Peek and others have shown that humidity does not affect the flashover voltage for sphere gaps and the authors of the paper have shown by their Fig. 6 that the flashover between wire loops is also not influenced by humidity.

Lewis' tests were made in a very large open room. The authors of the paper made their tests in a large box in order to be able to control all conditions of temperature and humidity. Lewis has just completed a large box of somewhat different dimensions and will soon have some further results made therein.

The authors made their tests with pins and wires or wires as electrodes. Lewis' tests were made with parallel plates in which edge effects were avoided by the use of large radii of curvature as shown in Fig. 4 herewith.

Schwaiger, whose work has been mentioned, used electrodes similar to those used by Lewis and obtained results in the same direction, *viz.*, indicating a decrease of flashover voltage with increased humidity.

The distinction between the results found by both Schwaiger and Lewis and those obtained by Littleton and Shaver seems then to be rather one of field form than one of humidity, or at least is certainly a function both of humidity and field form.

A possible explanation of this difference is one based on the shielding effect of corona. That is in the case of wires as used by the authors of the paper, corona voltage comes before arc-over. Under the conditions of test the added humidity or moisture content of the air permits a more uniform and a more abundant corona glow on the electrodes or even at edges of the insulator. This glow has the effect of readjusting the electric field so as to reduce the gradient, by a shielding effect thus increasing flashover voltage as the moisture increases.

When uniform fields are used as was done by Lewis and by Schwaiger there is no effect of this kind because flashover occurs at a voltage less than required for corona. Hence an increased moisture content of the air means an increased moisture deposit on the insulator with a corresponding decrease in flashover voltage.

Because of these facts it seems inadvisable to introduce in the A. I. E. E. rules for testing insulators any general correction constant for making humidity corrections because it seems apparent that humidity correction constants can at present be made only by the establishing of a correction factor for each type, and possibly even for each size of insulator; that is, with our present knowledge of the fundamentals involved we certainly are not in position to establish correction factors for humidity which will be applicable to insulator testing.

**J. T. Littleton and W. W. Shaver:** Several points have been raised in the discussion that require some explanation.

Mr. Lloyd referred to the slopes of the curves as being determined by the insulator designs and not dependent on a property of the surface of the material. This might very well be the case. However, our statement that the difference between the slopes of the curves for the Pyrex insulators and for the porcelain insulators of comparable size might be due to the difference in surface resistance of the material, has as we believe some foundation. It is very evident that the slope of the curve for the Pyrex No. 161 insulator is somewhat less than the slope of the curve for the porcelain 16-kv. insulator. These two insulators are almost identical in form and size. Also the porcelain 44-kv. insulator is quite comparable to the Pyrex No. 401 insulator and the slopes of the curves for these insulators are noticeably different. In this case, however, there is more difference in insulator shape than in the former case.

While the surface of both the Pyrex insulator and the porcelain insulator is a glass, these two glasses are very decidedly different in composition and undoubtedly have large differences in properties. It is well known that the surface resistance of all insulators depends upon the humidity. Even a material such as fused quartz shows a very large humidity effect, so that a difference in the surface resistance of porcelain and Pyrex insulators would be expected. However, it is not believed that in either case any chemical reaction takes place between the water vapor and the material.

Mr. Eby called attention to the fact that even under extremely dry conditions the flashover potential was not reduced to a value below the wet-flashover value and he concluded therefore that humidity curves were desirable only for the purposes of rating the insulators and really had no bearing in actual service. However, there is another point that must be considered and that is the allowable safety factor for a puncture given by the ratio of puncture voltage to dry-flashover voltage. For, instance, an insulator having a dry-flashover potential of 125 kv., tested in air to that point might under extreme conditions have a flashover value of 180 kv. in air which might conceivably be very near the puncture voltage; at least the factor of safety so far as puncture is concerned would be greatly reduced.

We do not understand exactly what Mr. Clark has in mind when he refers to a test made on insulating surfaces under oils of various moisture contents and we do not see in just what manner such tests may be applied to our data. Flashover tests made on a paraffin-coated insulator under various humidity conditions showed the same results as the uncoated insulator tending to prove that there is no chemical combination between the insulating material and the water which gives rise to the curves obtained. While the explanation of this phenomenon is undoubtedly of interest, that feature has been given but slight consideration by us. We believe that the additional conductivity of the surface of the material caused by the film of adhering water molecules has redistributed the field to a certain extent, tending to prevent an overstress of the air around the tie wire and along the surface of the material. Mr. Clark, however, is mistaken regarding the relative value of the dielectric constant of Pyrex insulators and porcelain. The dielectric constant of Pyrex insulators for 60-cycle frequency is about 4.8 which is decidedly lower than any figure which we have seen published for porcelain.

Attention again should be called to the fact that in studies of this type absolute humidities and not relative humidities should be considered. Measurements taken at a given temperature and given relative humidity will be quite different when taken at the same relative humidity and at a different temperature. There is almost twice the amount of water present in air at 25 deg. cent. as in air at 14 deg. cent. with the same relative humidity.

Mr. W. A. Lewis referred to the discrepancy between our results on rods and those of Schwaiger. We did not discuss Schwaiger in more detail inasmuch as his conditions did not duplicate ours, he dealing with uniform tangential fields and we with conditions as described. The fact that the results differ proves the conditions of the two experiments to be different. We trust that Mr. Lewis will make measurements on vacuum-dried rods, eliminating the temperature effect to which he has called attention.

There is, however, a doubt in many minds that the gradient in a field between parallel plates is uniform for there is some evidence that the drop in the neighborhood of the plates is very much greater than in the center of the region between them.

In our paper we state that a constant humidity was maintained for 15 min. before measurements were taken. It was our experience that this was ample. Mr. Lewis' curve further indicates that to be so, for a certain portion of his 40-min. interval is required for cooling. We did not call attention in our paper to a number of tests made on oven-dried insulators carefully cleaned with absolute alcohol, for the results after a sufficient length of time had been allowed for cooling, were identical with regular stock.

Professor Sorensen calls attention to the difficulty in arriving at a correction factor for humidity effect. His conclusions are identical with ours. The fact that our family of curves showed no consistency in change of slope proves that the humidity effect is dependent upon something beyond the absolute flashover potential. It probably depends upon the air path and the distribution of potential over the surface leakage path, in other words, the shape, and the surface resistance coefficient of the material. We believe that these factors can be separated and evaluated but the problem is by no means a simple one. For that reason we suggest a humidity curve as being by far the more simple way of evaluating this effect for any given type of insulator.

# The Cathode Oscillograph as Used in the Study of Lightning and Other Surges on Transmission Lines

BY HARALD NORINDER[1]

***Synopsis.***—*Visible records of the effects of lightning surges and transients on transmission lines are described in this paper, which explains the operation of a specially constructed cathode-ray oscillograph. The outstanding feature of this oscillograph is its ability to record phenomena of a microsecond in duration, while at the same time the instrument is maintained in an exposed position for as much as a million times as long as the occurrence. Methods of eliminating load frequency are discussed. Different types of lightning surges are reproduced. The use of the oscillograph for making graphic records of switching surges on transmission lines is also demonstrated.*

* * * * * *

## I. Research Studies of Lightning Surges on Transmission Lines

EVER since electric energy has been transmitted by long transmission lines extended over great areas, research into the nature of lightning surges has constituted a problem of great importance. The difficulties of a solution to the problem have been in many ways almost insurmountable.

*The limitations of a purely theoretical solution to the problem of lightning surges.* Several attempts have been made to solve the problem of surges on transmission lines in a purely theoretical manner. Such a solution has been a necessity for the formal consideration of the effects of surges running in a transmission network with given line constants. The limitations of such theoretical calculations reside particularly in the fact that assumptions have to be made as to the nature of the surges in their initial moments. Evidently it is of vital importance to know the amplitude and the sloping of the surge front, while a knowledge of the front characteristic is of fundamental importance when, for instance, the reactions of a surge into a transformer must be taken into consideration.

*Practical value of a direct study of lightning surges.* It is, however, not a purely theoretical point of view that has stimulated a direct study of lightning surges on transmission lines. The problem is of more interest in relation to the practical engineering demands which have stimulated research work on lightning surges. On a transmission system, it may, for instance, be quite necessary to make a decision as to whether or not it is necessary to use lightning arresters. Or it may be necessary to take up a comparative study of the protective value of different lightning arresters. In such a situation, it is evidently quite important to be acquainted with the nature and the different forms of the lightning surges. The same holds true for the construction of lightning arresters.

*Some special difficulties in a direct study of lightning surges.* It is not a lack of interest that is responsible for our shortcomings in understanding lightning surges. Our failure has another explanation. There are many experimental difficulties in direct research work on transmission lines. This is especially the case when we try to secure direct evidence of the nature of surges, etc., under full load conditions on a line. In many earlier research studies we have attempted to eliminate these difficulties by indirect methods. For instance, the damage wrought by lightning surges on transformers, wall bushings, etc., has been observed and from such observations we have derived some knowledge of the frontal characteristics of the surges, their oscillatory character, and their amplitudes. It is a well-known fact that in most cases a flashover is a chance occurrence, and thus it is not easy to derive valuable conclusions from such an empirical consideration of the surge phenomena.

A valuable solution can be arrived at only by direct research where the natural conditions of the surges are observed under full load conditions. From this demand for research under load conditions, some special difficulties arise, as we shall see.

*Need for a suitable instrument in studying surges on a line under load.* When research study of lightning surges is limited to an observation of their amplitudes and their character of polarity, good results have been gained by the klydonograph.[2] But when it is necessary to give an exact analysis of the wave shape with regard to time, the only possible instrument now developed is a suitably constructed cathode-ray oscillograph with an electron jet directly bombarding a photographic sensitive layer situated within an evacuated vessel.

*Difficulties with earlier instruments.* The following demands must be met by the specially constructed cathode oscillograph:

1. As the oscillograph must record surges which are generated without the control of the operator, it must be so arranged that a record is possible for the shortest times of passage $10^{-6} - 10^{-8}$ sec. with a single passage of the phenomena.

2. As the time of arrival of surge phenomena cannot be known by the operator, the instrument must be so arranged that it can be in a continually exposed position for time periods a million times as long as the time necessary for the recording of the surge.

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[1] Royal Board of Waterfalls, Stockholm, Sweden.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., February 13-17, 1928.*

[2] J. H. Cox, P. H. McAuley, L. G. Huggins, TRANS. A. I. E. E., Vol. XLVI, 1927, p. 315.

3. The instrument must be so arranged in construction and manipulation that its electron emission is steady and sufficient. Instrumental and accidental disturbances must be eliminated.

A cathode-ray oscillograph with a photographic sensitive layer in vacuum was first constructed by Dufour. His excellent instrument has given very good results in the study of such transients and oscillations where the time of arrival was determined by the operator. The oscillograph has thus been used for study of the time lag of sparks and for proper oscillations of transformers.

In the study of lightning flashes and the surges produced by them on transmission lines, however, it has not been possible for us to use an oscillograph of the Dufour pattern. The total time of exposure in such an oscillograph is restricted to a few times the total time of duration of the surges because of the excessive blackening of the film which would otherwise occur. Since it is impossible to foretell the exact time a lightning surge will occur, it is necessary to have a time of exposure of sometimes half an hour or more in order to record a surge with a duration of fifty microseconds; it can easily be seen that it was quite necessary to solve the research problem by elimination of the blackening effects of the electron jet.

*The oscillograph especially constructed for transients and surges on transmission lines.* In the beginning of our research work on lightning surges in the laboratory of the Swedish Royal Board of Waterfalls, we were soon persuaded that the conditions given above could be met only by an instrument of special pattern. If the occurrence of lightning flashes and of their surges on transmission lines had been very frequent in Sweden, we should probably have been able to obtain results earlier. During some seasons, however, we have only one or two occasions to secure records, which is not sufficient, considering the experimental difficulties that must always be related to the problem.

Fig. 1—The Cathode Ray Oscillograph of New Construction

The instrument which we devised in the research station of the Royal Board of Waterfalls near Uppsala is illustrated in Fig. 1.

The instrument is, as may be seen, very robust in its construction. It consists mainly of metal, using only a straight bit of glass between the cathode and the anode. A suitable vacuum pressure can be regulated by the aid of a specially constructed regulation valve. By this arrangement, it has been possible to establish a very steady electron emission from the cathode.

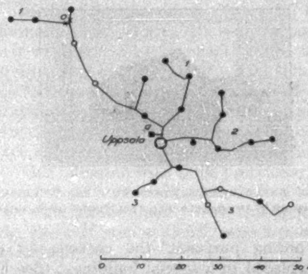

Fig. 2—Map of 20-Kv. Transmission System Used in Recording Lightning Surges

All arrangements have been made to secure a continuous operation with the instrument. The necessary time for evacuation has been considerably reduced. Valves and vacuum tubes have been constructed of metal and the pump connections to the oscillograph have been so arranged that it is not necessary to stop the pumps when passing air into the oscillograph vessel for changing films. The pump arrangement is so effective that it is possible to gain an effective vacuum within 8 to 10 min. with a film surface of 600 sq. cm.

Special arrangements make it possible to reduce the secondary stray radiation from the electron jet, and thus it is possible to work with the oscillograph in an exposed position for one or two hours. During this time of exposure, the instrument still has the property of recording short transient phenomena with a total duration of some millionths of a second. It is quite possible to attain still shorter times by a regulation of the intensity of the electron emission.

In the following will be demonstrated the results gained with the instrument in recording either lightning surges on a transmission line or switching surges under full load conditions The records were taken with the cathode oscillograph connected to a 20 kv. transmission line from a transformer station of the Royal Board of Waterfalls in the vicinity of Uppsala, Sweden. The short connection line from the experimental station to the transmission line is marked *a* in Fig. 2.

*The connection of the oscillograph to the transmission line under load.* The records of lightning surges were taken mainly from the transmission line group marked No. 1 in Fig. 2. Sometimes surges coming from lines 2 and 3 were also recorded. By the connection of several end points of lines to the record system, it sometimes has been difficult to identify the reflected surges.

FIG. 3—THE EXPERIMENTAL STATION OF THE SWEDISH ROYAL BOARD OF WATERFALLS FOR THE STUDY OF SURGES

For recording purposes, the cathode-ray oscillograph was placed in a special building. (See Fig. 3.) The distance between this building and the line was 50 meters, and from the connection point to the transformer of the line was 150 meters. The records thus can be referred to one of the end points of the line.

The oscillograph was connected through condensers to the line, the connection consisting of two chain insulators for each phase. Their capacity was 20 micro-micro-farads and thus could be neglected in comparison with the line capacity. It was easily possible to disconnect the line voltage from the system by the aid of an outdoor switch. (See Fig. 3.)

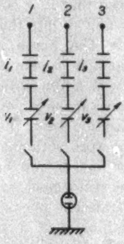

FIG. 4—METHOD OF THREE-PHASE CONNECTION OF THE OSCILLOGRAPH TO THE TRANSMISSION LINE

*Methods of eliminating load frequency.* The measurements were performed under full load voltage and thus it was necessary to make use of an elimination method for the 50-cycle voltage. For this purpose we used different methods.

1. The three-phase voltages from the line were reduced by the capacities of the identical surge insulators, $i_1$, $i_2$, $i_3$, and the small variable air condensers $v_1$, $v_2$, $v_3$. (See Fig. 4.) A small distortion of the line voltages caused by load variations in the transmission lines was easily eliminated by regulation of the variable condensers $v_1$, $v_2$, $v_3$. When the system was in full phase symmetry, the sum of the voltages was zero. And then, if for instance the symmetry were disturbed by an atmospheric surge, a deviation of the electron jet took place within the instrument. (See Fig. 5-a.) This method has a disadvantage. If the surge should cause a breakdown to ground on one of the three phases, the load voltage from the other phases would cause a blackening of the film.

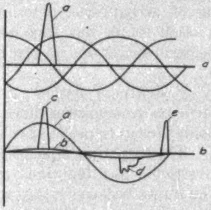

FIG. 5—TWO DIFFERENT METHODS OF DIMINISHING THE EFFECT OF LOAD FREQUENCY

2. The oscillograph was connected in single phase to the line, for instance, above the variable condenser $v_1$, from line 1. (See Fig. 4.) The two other lines, 2 and 3, were disconnected from the oscillograph. By regulation of the small air condenser $v_1$, it was easy to give such a value to the line voltage that it was covered by the "zero losses" of the oscillograph. (By zero losses is meant that amount of voltage that must be imposed on the instrument before any record takes place.) The line voltage was in such a case reduced from the initial value *a* as in Fig. 5-b to the reduced value *b* in the same figure. Surges *c*, *d*, or *e* exceeding the line voltage could in such a case be recorded. The advantage of this method lies in the great deviation possibilities of the surge above the line voltage and an easy control of the latter, while the normal load voltage varies only within the fixed zero losses of the instrument, which may be between five to ten per cent of the whole possible deviation of the instrument.

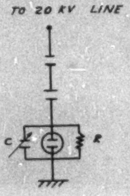

FIG. 6—METHOD OF DIMINISHING THE EFFECT OF LOAD FREQUENCY BY MEANS OF LEAKAGE RESISTANCE

3. The oscillograph is single-phase-connected to the line. (See Fig. 6.) Parallel to the deviation system of the oscillograph is placed a leakage resistance $R$ and a small variable condenser $C$ of such a value in relation to the capacity of the system that it affords an effective leakage for the load frequency, but stops higher frequencies, for instance, those of 1000 periods or above. The leakage of the resistance diminishes with the increasing of the frequency. For an effective regulation, it is still necessary to hold the reactance of the condenser small in comparison with the leakage resistance. If a set of impulses is observed and their time of duration is shifting, difficulties may arise in using this method. The reactance of the condenser system varies with $\omega$, and it is thus quite impossible to get a value for the leakage that can be considered as suitable for a very much wider range of frequency. This may be seen by the relation:

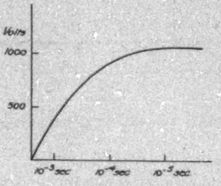

FIG. 7—VOLTAGE CORRECTION CURVE FOR DIFFERENT FREQUENCIES

$$V_R = V e^{-\frac{2\pi}{R\omega C}} \quad (1)$$

where $V$ is the voltage between the condenser plates without leakage, and $V_R$ the corresponding voltage with leakage. The leakage resistance is $R$, the effective capacity $C$. When recording with variable frequencies, it thus must be noted that the functional correlation between the leakage and the frequency can be represented by a curve. (See Fig. 7.) The modification by the leakage is illustrated by Fig. 8, where curve $I$ represents a real curve and curve $II$ the modification of amplitude that results from the leakage of the resistance $R$. The regular variation of the voltage with the frequency makes it possible to establish corrections for a defined frequency. It is always possible to give such a value to $R$ and $C$ for a given frequency that the influence of the leakage can be reduced.

In order to reduce the influence of and errors caused by unknown variation with high frequency of the leakage resistances used, it was necessary to test the leakage circuit by superimposing on the system at the high voltage end, voltages of known frequency and amplitude from a separate impulse generator.

*Results of the measurements.* In the following will be revealed the results of studies of lightning surges made at the above-mentioned experimental station at Uppsala. The general direction of these results has been clear to us for the past four years. By visual observations of the fluorescence spot in the cathode-ray oscillograph connected to transmission lines, we have obtained a first-hand practical experience of the frequency and the variation forms of lightning surges on transmission lines. From this experience we had to decide the velocity to be used in recording lightning surges. In this first research work, we did not prefer an abnormally high velocity for making our records, because it was clear to us that many of the surges had their fronts not quite straight, but sloping. The probable reflections from different points of the transmission system were another reason for our making our records with a velocity that was not too high. In such a case, too high a velocity would cause a confusion of the curves. Our intention with these preliminary research studies was to get a general understanding of lightning surges on transmission lines. With this general understanding, the next step evidently was a more detailed study of the surges.

A feature which we noticed in the beginning of our observations was the following: Sometimes severe thunderstorms developed in the vicinity of the transmission lines without any appreciable occurrence of lightning surges on the transmission lines. The explanation of this circumstance should be plain enough. The general distribution of the field intensity in the thunder cloud was such that either no field lines that were broken down by the lightning flashes ended on the transmission lines, or the breaking down of the lines was performed with such a slow velocity that no lightning surges of any appreciable amplitude could be developed. On another occasion, a similar thunderstorm might develop plenty of surges following one after another on the same transmission line. In such a case, the general field distribution was of a peculiar character, with many field force lines ending on the line, and the lightning flashes developed in as short a time as was necessary to produce surges. Sometimes we could observe surges following one after the other where all were of the same shape. This might be explained by the fact that the lightning strokes were developed during similar physical conditions within a restricted sphere of the thunderstorm cloud.

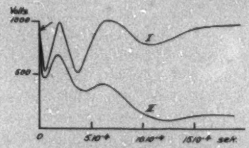

FIG. 8—APPEARANCE OF SURGE WHEN USING LEAKAGE RESISTANCE METHOD

It must be noted that our observations of the lightning surges have been hindered by the infrequent occurrence of thunderstorms in Sweden. During the season of 1926, we could get only a few surges on our transmission lines which were under observation. Thus we were forced to economize with the few opportunities for observation which were available, and it was necessary to develop our instruments to a high degree of operating safety. Especially were we obliged to concentrate our efforts on the point of eliminating the secondary stray radiation in order to get the longest possible time of exposure.

*The first lightning surges recorded with the specially constructed cathode oscillograph.* The first records of lightning surges were taken during the summer season of 1925. A specimen of such a record is given in Fig. 9. The normal 50-cycle load in this case varied within the limits of the bright band. We can observe from the curve surge values of about three times the top values of the load voltage. When these records were made, the cathode ray oscillograph was not so highly developed with regard to elimination of secondary stray radiation and intensity of the electron jet. Therefore in making the record in Fig. 9, it was necessary to hold a relatively small electron emission, which reduced to some degree the sharpness of the curves. For reproducing this oscillogram in a printed paper, it was necessary to intensify to some extent the curves of the original record.

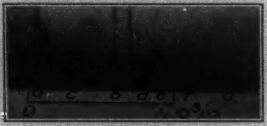

Fig. 9—First Oscillograph Record of Lightning Surge on a Transmission Line

We can see in *a* and *b* of Fig. 9 two different surges with their fronts quite straight. The reflections of these surges are also visible, for the first surge *a* at *c*, and for the second surge *b* at *e*, *f*. The curves with small amplitudes at *d*, *f*, and *g* must have their origin in other surges that have been highly damped before reaching the point of observation. The reflected surges have undergone, as we can see, a very pronounced damping. The initial top value of the surge was more than three times the normal line voltage to earth. In spite of these high surge values, the protective relays did not cause any disconnection of the transmission line. We can, in such cases, suppose that flashovers occurred on some of the insulators of the transmission lines where the surge had its highest value, but the paths of flashovers were too weak to produce a connection strong enough to complete a connection to earth for the normal load voltage of the line. Similar situations have been observed several times.

*Various lightning surges which were recorded on transmission lines during the thunderstorm season of 1927.* Improvements in the cathode-ray oscillograph made it possible to record many surges on transmission lines during the summer season of 1927. The oscillograph was connected through condensers to the line either in a single-phase connection or sometimes a three-phase one. The records of the latter connection were sometimes disturbed by a current to earth from some of the connected phases. The recorded surges were in such a case covered by the 50-cycle load voltage variations and it was sometimes troublesome to identify the surges in the primary records.

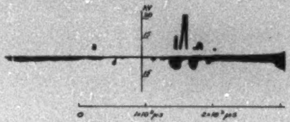

Fig. 10

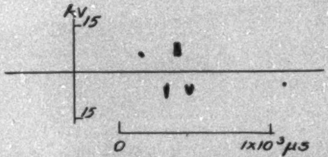

Fig. 11

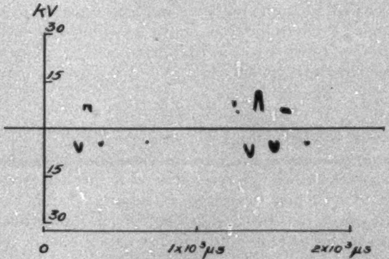

Fig. 12

Figs. 10, 11, 12—More Recent Records of Lightning Surges, Taken With an Improved Instrument

As may be seen by the following reproduced records, we sometimes have records of surges with a small amplitude. The reason for this is that since relatively few thunderstorms produced surges on the transmission line, it was necessary to work with thunderstorms often far away from our observation station. A lightning surge with an initially high amplitude at, for instance, 30 km. distance from our observation point thus reached the oscillograph in a damped state.

In Figs. 10, 11, and 12 are given some examples of surges recorded on the 20-kv. line mentioned above. These figures are direct reproductions of records with the film in an exposed state in the oscillograph's vessel during an hour. In spite of the long exposure time, we can not find any trace of severe blackening by secondary stray radiation.

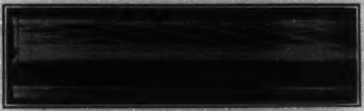

Fig. 13—Oscillogram of Lightning Surges, Obtained by Using Three-Phase Connection of Oscillograph

In Fig. 10 there are several surges superimposed in the same period of record while the surges in Figs. 11 and 12 are separated. The surges of Fig. 12 seem to have an oscillatory character caused by special connections in the transmission line system.

The method of a three-phase connection has also been used and in Fig. 13 is a record reproduced where the oscillograph was connected to the three phases of the line through suitable condensers. The earth current in this case gave rise to a dissymmetry of the phase voltage, which to some extent disturbed the record. In other original films it is possible to find several surge types of interest. In Figs. 14 to 16 some of them are given, drawn from the original records taken with a three-phase coupling. The earth current in these records caused a dissymmetry in the load voltage and in such a case a direct reproduction would not give a clear view of the recorded surges.

*The different types of lightning surges and the need for more extensive research in the future.* The different types of lightning surges that we have recorded are demonstrated in Fig. 17. About one-fifth of them have, as in No. 1, a straight front where the highest voltage is reached within a few microseconds or part of a microsecond. We hold it as possible that some surges of this type are generated by direct lightning strokes on the lines. At the very moment some of them were produced, we have observed lightning strokes in the vicinity of the transmission lines.

The other surge types 2 to 5 of Fig. 17 reach their highest value in a time varying from 10 to 150 microseconds. Surges of a highly damped or oscillatory character, types 3 and 4, we have observed only a few times when the line was disconnected by the protective relays. Type 5 has been observed during similar conditions.

A marked variation in wave shape and frontal characteristics of the lightning surges recorded has been observed. This variation is fully explained by the unstable conditions which sometimes are characteristic of the electrophysical development within a thunderstorm cloud. The discharging processes within a thundercloud take place often only between charged cloud volumes. In such a case, lightning surges may be produced where the front is sloping. On the other hand such discharges between cloud volume and the earth may produce surges where the fronts are quite steep.

Pronounced positive surges such as 1 and 2 in Fig. 17 are the most frequent type. Sometimes such surges were followed by earth current in the line. We have often held our film in an exposed position a long time in order to get as many surges as possible; thus it is clear that earth currents from some of the heaviest surges could not be avoided. Very often the repeated surges were of type 5, having a similar amplitude value; therefore, they cannot be regarded as reflected phenomena from an original surge. In Fig. 9 on the other hand, there can be noted a fixed time difference between the original surge and its reflections. That the time between an original surge and its reflections may vary from case to case, can be explained easily. The thunderstorms

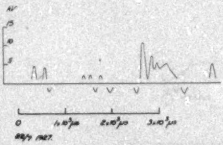

Fig. 14

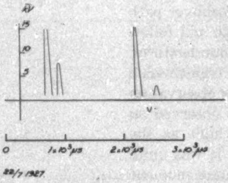

Fig. 15

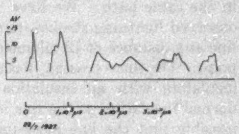

Fig. 16

Figs. 14, 15, 16—Reproduction of Several Interesting Surge Types Recorded

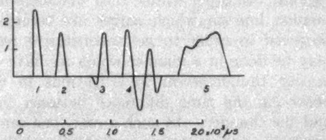

Fig. 17—Different Types of Lightning Surges Recorded With the Cathode Ray Oscillograph

considered as a generating region of the surges may, of course, change their distances from the transmission line, and sometimes we must calculate with two thunderstorms at a distance along the same transmission line. Therefore we can explain the differences in time from the reflected transients. Characteristic of the reflections is the pronounced damping.

The amplitudes of the surges have varied between 5 to 30 kv. to earth, values from ½ to 3 times the normal load voltage to earth. A number of our recorded surges has a remarkably low amplitude. This may be explained by our special precautions in these researches. We have tried to get as many surges as possible, and we have not restricted our efforts to such surges as have an amplitude surpassing the line voltage.

We have already pointed out the marked damping of many surges. In some cases, we have found a damping to 1/10 of the initial value on a distance of 60 to 80 kilometers. Surges that are developed at a distance of 30 to 40 kilometers from our observation point must, when they are passing this point, already be damped to some extent.

A surge exceeding three to four times the line voltage to earth does not necessarily produce a flashover path of such concentration that the line voltage will follow in the same path. We have, during a thunderstorm, observed lightning strokes quite near the transmission line at a distance of 12 kilometers from our observation point. On this occasion, flashovers were observed on insulators with an insulation twice as high as the normal insulation of the line insulators. It was quite possible that the line insulators at the same moment flashed over. Any disconnection of the lines by the protective relays at that moment was not observed.

An object to be desired in future research studies is to work with a set of oscillographs at different distances along the line, and at the same time put up one or two oscillographs especially adapted for recording the discharge forms of the lightning.

It is of importance with regard to the future to observe the real location of the lightning channels and regions. In other words, their distances to the transmission line on which surges are recorded must be observed in order to get quantitative results. This may be done in a manner which we have earlier used in our thunderstorm investigations in Sweden, by observing the time difference between the lightning and the thunder. In such a case, one can use two or three observation stations suitably located with regard to the transmission lines.

While our studies of lightning surges on transmission lines have fully confirmed our earlier results that were drawn indirectly from the nature of lightning discharges, we cannot yet draw positive conclusions about the character of surges on transmission lines. The primary set of phenomena that controls the generation of surges on transmission lines is quite variable. It is therefore necessary to do an extended piece of work before we are ready to deprive the surges of all their mystical character. From the results given above, it is evident that it is now possible to undertake an exact piece of research on the lightning surges on transmission lines in an entirely different manner than has heretofore been feasible.

## II. STUDIES OF SWITCHING SURGES ON TRANSMISSION LINES

For some time it has been desired to record such transients as are produced by switching on long transmission lines. The difficulty of such studies has always been the lack of suitable instruments.

*The limitations of purely theoretical calculations.* By theoretical methods it has been possible to precalculate the general characteristics of transients. Such a calculation, however, has its limitations. By calculations, only, we can get no answer to the question as to what happens in reality on a transmission line during a switch operation under full load conditions. Several experiments have been made with artificial lines to escape this difficulty. The line constants have in such a case been chosen so that they correspond in their oscillations to the proper oscillations of oscillographs of the usual pattern where the vibrating element is a mechanical one. Such studies have served to confirm the theories of transients, but they cannot give any answer as to what happens on a line during switching with full load conditions.

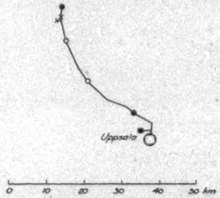

FIG. 18—DIAGRAM OF 20-KV. LINE USED IN TAKING OSCILLOGRAMS OF SWITCHING SURGES

*Switching transients graphically recorded by suitable cathode ray oscillograph.* The uses of the cathode ray oscillograph in recording lightning flashes and surges having been made clear in the first part of this paper, it will be evident that the cathode ray oscillograph constitutes a suitable instrument also for recording switching surges on transmission lines under full load conditions.

*The transmission line used for switching surges.* For the switching operations, we have used a 20-kv. line of which a diagram is given in Fig. 18. At one of its end points, the line has been connected to a commercial transformer of a ratio of 70/20 kilovolts.

The neutral point of the transformer has been earthed directly without any ground resistance. The line has been set free from all inductive loads in the form of transformers and the other end of the line has been open. In order to get as pure conditions as possible, all side branches of the line have been disconnected. Sometimes two of the three-phase lines have been connected in one of the line ends in order to get a double length of the line. For the switching operations, we have used commercial oil switch-breakers which, in general, have not been equipped with discharge resistances.

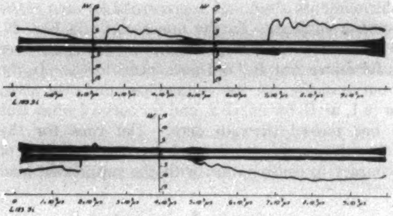

FIG. 19

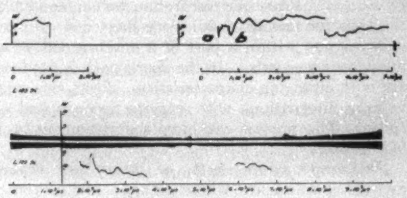

FIG. 20

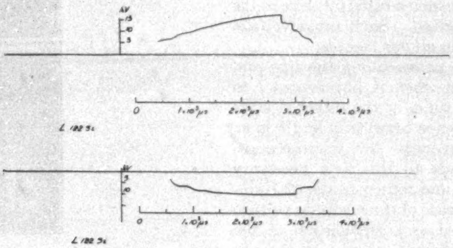

FIG. 21

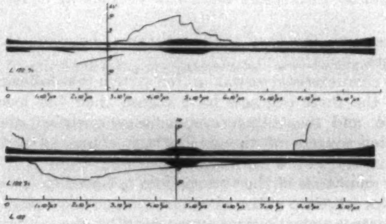

FIG. 22

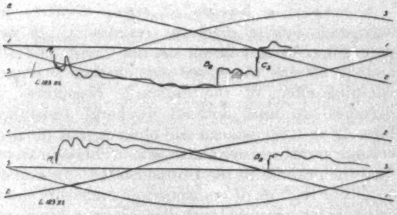

FIG. 23

FIGS. 19, 20, 21, 22, 23—OSCILLOGRAMS OF SWITCHING TRANSIENTS, USING THREE-PHASE COUPLING METHOD

*Methods of eliminating the normal load frequency.* The measurements have been performed either with a single-phase or a three-phase connection to the line, and we have in these investigations used the methods of elimination that were described in the first part of this paper. The latter type of connection has sometimes been of great value, because it is possible by this connection to eliminate the ordinary 50-cycle load voltage in a simple way. If the system has its full symmetry, the resulting voltage must be zero on the deviation system of the oscillograph connected through condensers to the transmission line. In such a case, when the symmetry is disturbed, we can get a voltage on the deviation system and thereby get a record. We have found this method very simple and convenient for the elimination of the ordinary load voltage.

*Results gained on commercial lines under load conditions.* Our experimental studies have been executed on commercial lines under full load conditions. This has been a circumstance both of advantage and of difficulty. By switching with a commercial breaker on a particular line, we have gained phenomena of similar character, and it has been impossible to vary the operations with regard to the amplitude and the front sloping of the transients. The method has its definite advantages. It has been possible by this method to gain such transients as really occur on transmission lines under natural load conditions. Some variations and irregularities have been observed. These are caused by irregularities lying in the arcs and sparks of the oil switch. For instance, in closing a circuit breaker, the contact at a certain moment will be separated sufficiently to cause a spark, which is followed by an arc. From our researches, we can conclude that the time for this spark is a very short one—the process is developed within a part of a microsecond, or within a few microseconds. In the spark path is produced an arc with changing characteristics. From this originate voltage fluctuations with varying periods and amplitudes. The process can have a duration up to 1/500 of a second.

*Switching surges with a three-phase connection.* Switching transients, where we have used a three-phase coupling method, are produced in Figs. 19 to 22. From Figs. 19 and 20 may be seen a rapid increase in the voltage when the line energized. Such rapid voltage variations can be observed in all our records.

This straight front wave passes along the line and can very often be observed when it is reflected. In Fig. 20 we can observe the time for the reflected wave marked *b*. The time difference between *a* and *b* is as measured on the original records 280 microseconds, which altogether corresponds to the time necessary for a transient wave to pass and return on the 42.1-km. long line. The marked increase of the resulting voltage at *b* can easily be explained as a summation of the existing voltage and the reflected voltage at the observation point.

*A comparison between oil circuit breakers provided with and without discharge resistances.* If we compare Figs. 19 and 20 on the one hand, and Figs. 21 and 22 on the other, we can observe a pronounced damping effect of the discharge resistances. If oil switches are used without discharge resistance (see Figs. 19 and 20), we can still observe that the produced voltage variations are not severe. This is in accordance with the practise in the United States. An examination of all our records of transmission transients shows that breakers not provided with discharge resistances produce more rapid voltage variations in comparison with those having resistances mounted. It seems that the difference is not great enough to give any reason for the complications and costs that always follow the existence of the discharge resistances. In their initial moments, voltage transients are developed with straight fronts. The amplitudes of these voltage surges do not exceed the variation of the load voltage.

*The advantages of using a three-phase coupling method.* The method of using a three-phase connection through condensers has some advantages over the method of a single-phase connection. The former method can give a more general view of the switching phenomena recorded. This can be seen by the Figs. 23 and 24. The time covered by the record in these figures extends over half a cycle of the normal load frequency. In order to explain the records of Figs. 19 and 20, we have drawn the three-phase half periods together with the switching transients with marked initial times. It is easy to observe, by comparison, how the moments of contact are recorded for each of the three-phase voltages. In the upper curve in Fig. 23, we can see that the voltage of curve 1 has gone over at $A_1$, for curve 2 at $B_2$, and for curve 3 at $C_3$. In the lower curve in Fig. 23, the voltage has gone over at $A_1$ for curve 1, at $B_2$ for curve 2, and for curve 3 when this curve has passed through zero. The time for the contact voltages is determined by the position of each contact in combination with the suppressed load voltage and the insulation resistance between the contacts.

Fig. 24—Oscillogram of Switching Transients, Using Single-Phase Connection and a Low Leakage Resistance

The characteristic method of the system is as follows. When the three contacts have gained their full load voltage, and the voltage system is symmetrical, the deviation system of the oscillograph comes to zero potential.

The amplitude of the voltage does not need to come up to its full crest value when the contact takes place. The contact value is determined both by the voltage value of the contact and its position with regard to the insulation resistance of the oil.

*Results of switchings where the single-phase method has been used.* The other method used was a single-phase connection. In this case, the other two phases were either grounded, or in some instances, insulated. Some definite difficulties arose in the use of the single-phase connection method. It thus was necessary to eliminate the normal 50-cycle load voltage. For this purpose, we have the method with a leakage resistance already described. We must remember that this method gives different voltage scale values for different frequencies.

We have not, in these researches, found it necessary to introduce a variable voltage scale. Our scale given in the figures thus refers only to the voltage fluctuations of a voltage variation where full voltage values are gained within about a hundred microseconds.

Some researches with a single-phase connection are reproduced in Fig. 24. In these records we have used a very low resistance and the leakage thus has been appreciable in order to record only the rapid voltage variations. The length of the line was 42.1 km. The straight voltage fronts, that are clearly visible on the original records, are marked *a* in Fig. 24. The voltage reaches its full value within a few microseconds and these curves are then marked *b* after reflection from the other end of the line. The time difference between the original and the reflected curve is 280 microseconds, a value in full accordance with the normal speed of transients on the line.

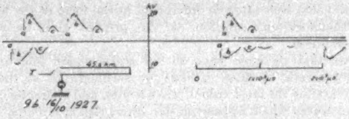

FIG. 25

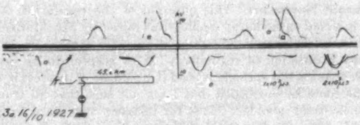

FIG. 26

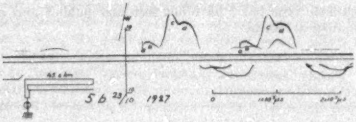

FIG. 27

FIGS. 25, 26, 27—OSCILLOGRAMS OF SWITCHING SURGES, USING SINGLE-PHASE CONNECTION AND LARGER LEAKAGE RESISTANCE

Some studies have also been made where a larger leakage resistance is chosen than in the case first mentioned. By such an arrangement, it has been possible to record slower voltage variations. The line length has been doubled in this measurement.

Some results of such measurements are given in Figs. 25, 26, and 27. The line length and connection diagrams are given in these figures. The straight initial voltage front that is developed when the line was set under load is marked *a* in some of the Figs. 25 to 27. This straight front varies with its full value within a few microseconds and must, with the time scale used in the records, be marked as a vertical line going up from the zero line. These straight fronts are very quickly damped.

In Fig. 25 are reproduced a set of repeated connections of the line to the transformer. It must be noted that these different connections produce similar voltage variations marked *b* in Fig. 25. In connection with this slow variation, we observe a high frequency variation that is quickly damped. The reflected transient coming from the other end of the line is regular and marked *c* in the figures.

The voltage variations in the open end of the line have been recorded and are reproduced in Fig. 26. The initial voltage variations in this figure are marked *a*. As the line is open, we have recorded a doubling of the voltage amplitude. The high frequency which is very marked in Fig. 25 has quite disappeared at the open end of the line.

Voltage variations of a more complicated structure are reproduced in Fig. 27. In this record the voltage variations are composed of the initial, the passing, and the reflected voltage variations.

*Conclusions.* This article covers the first studies of lightning and switching phenomena with a cathode-ray oscillograph of new construction, ever made on transmission lines during load conditions. Naturally it is only a beginning describing some practical schemes that can be employed in making such investigations, and the author hopes that further work to be done in the near future will bring out many more valuable contributions to the science of lightning and switching phenomena.

## Discussion

**D. W. Roper:** In all of the calculations of the effects of lightning heretofore, it has been necessary to assume the shape of the wave of the transient voltage due to lightning as a basis for calculations. Similar assumptions must also be made in connection with the tests on lightning arresters with the aid of the so-called lightning machines, in order to obtain information regarding the relative protective value of various types of arrester. Now for the first time Dr. Norinder shows, not some assumed values, but some actual curves obtained by his modified form of cathode-ray oscillograph. These records show very plainly that there is a wide variety in the forms of transient voltage waves, and this means that it is not sufficient to assume one particular form of wave in making comparative tests on lightning arresters. Instead, the proper procedure would be to arrange the lightning-machine circuits so that a variety of transient voltage waves would be applied to the lightning arresters under test, and the average of the results obtained in this manner utilized instead of the results from one particular form of wave as has been the practise heretofore. In all probability, such a procedure will account for a part of the discrepancies which have been noted between tests on lightning arresters in the laboratory and the records obtained from arresters in service.

Recent studies of the transformer failures due to lightning in Chicago indicate beyond any reasonable doubt that about 30 per cent of such failures are due to transient high voltages which enter the transformer on the low-voltage leads. The failures from this cause, which are of the order of 0.1 per cent per year, are so small that it is quite impossible to secure the data by the statistical method that was followed in the papers heretofore presented before this Institute, and, accordingly, arrangements are being made to secure this information by means of a cathode-ray oscillograph similar to the one used by Dr. Norinder. It is hoped that, in addition to furnishing information as to how the transformer failures due to lightning entering via the secondary leads may be prevented or reduced under the conditions in Chicago, the studies which are planned will, in addition, furnish information regarding lightning protection which can be applied to higher-voltage circuits.

**K. B. McEachron:** Those who have attempted to solve the problem of applying the cathode-ray oscillograph to the study of lightning in the field appreciate the difficulties involved.

In the United States we have been operating oscillographs of the Dufour type over a period of three or four years, and have been quite successful in recording the performance of devices on transients produced in the laboratory. The difficulty comes about chiefly in the matter of getting the oscillograph under way when the transient comes along. Needless to say we have no premonition of its happening, and as a rule we are not able to beat the transient to the oscillograph, which means that we must have some means of automatically setting off the oscillograph, or else keeping it in operation all the time. Dr. Norinder seems to have solved that problem in the second manner. In that connection there is one question I should like to ask him. I presume he is using a cold-cathode-ray oscillograph, and I wonder how much difficulty he has with holding a good spot on the film. I assume he has no difficulty because his photographic records are satisfactory. We have had difficulty in that particular respect, in holding a satisfactory spot over a long period of time when using high cathode-anode accelerating potentials.

This problem can perhaps be attacked from the standpoint of the hot cathode instead of the cold. There are certain inherent difficulties with that method, however. In the Lightning Arrester Laboratory in Pittsfield we have worked out a scheme whereby the transient will actuate the oscillograph although the device itself was not previously in operation. By that I mean that there is no cathode stream at the moment the lightning discharge reaches the oscillograph, but it has been possible to set up the circuit so as to start the oscillograph at the moment when the transient appears. It is necessary, of course, to find some means of delaying the transient for a short period of time, as in the method Gabor used in his experiments in Berlin where he delays the transient by passing it through a cable of more or less known characteristics, and then measures the emerging transient. In the meantime the oscillograph has had a microsecond or two to get into operation.

We have come to feel that this problem is an extremely important one. Some valuable work has been done in this country with the Lichtenberg figures. However, they tell us nothing about the duration or tail of the transient and therefore we are unable, very often, to decipher accurately the results which we get from the surge-recorder or klydonograph studies. This is probably due very often to differences in the form of the waves, and therefore our solution at the present time is rather indeterminate.

I feel that we must have on our transmission lines in our country several of these cathode-ray oscillographs so that we can determine the crest values, wave fronts, and character of the tails of waves which appear on our transmission circuits. The effect of the station equipment in modifying and reflecting these waves forms should be also determined.

**Harald Norinder:** This question of the regulation of the spot in a cold-cathode-ray oscillograph raised by Mr. McEachron has not caused us any difficulties at all. To have a steady spot is only a question of regulation. With respect to an oscillograph where a hot cathode is used it would be of interest if such a type could be developed, but I am not sure that all troubles could be easily avoided. It is for instance very hard to get a suitable concentration through the anode with the hot-cathode type. There have been some trials to solve the problem of the hot-cathode type but I have not seen any publications giving good practical results.

# Synchronous Machines—IV

BY R. E. DOHERTY* and C. A. NICKLE*
Member, A. I. E. E. Associate, A. I. E. E.

***Synopsis.**—The special case of cylindrical rotor machines has been treated previously by Boucherot and others. The present paper solves the general case, including salient pole machines. The cylindrical rotor type thus becomes merely a limiting case. The principal assumption which distinguishes the present theory from the extensively studied cylindrical rotor theory is that the total armature self-inductance is here taken as variable with respect to rotor position, whereas the previous theory of short circuits, as represented by Boucherot, for instance, assumes this inductance to be constant—in other words, that the air-gap is uniform.*

*The four basic concepts underlying the improvement in theory, both as applied here and in the authors' previous work on Synchronous Machines, are:*

*1. Characterization of the machine by four reactance coefficients, two corresponding to the main pole axis, i. e., direct axis, and two to the interpolar axis, i. e., quadrature axis. These are:* $x_D$, $x_D'$, $x_Q$, $x_Q'$. *(See notation.) Thus the theory has been referred to, more or less aptly, as the "Four-Constant Theory."*

*2. Resolution of flux and m. m. f. waves traveling with respect to the rotor into stationary, pulsating components in line with the direct and quadrature axes. The theory involves also, of course, the usual Blondel resolution of the stationary fundamental waves.*

*3. That the variable component of armature inductance varies between the direct axis value and the quadrature axis value as a second harmonic function of the electrical space angle. This applies to all variable components of inductance which, with armature current of fundamental frequency, produce fundamental voltage.*

*4. The complete use of a fractional system of notation throughout the equations, thus expressing each quantity as a decimal fraction of some definite, convenient value, such as "normal" value. This is, of course, an outgrowth of the familiar practise of expressing such quantities as a per cent of normal value, but the latter involves carrying along the "100" in calculations, which is both cumbersome and conducive to numerical error. Experience has established a very definite preference for the former—the only difference between them, of course, being the position of the decimal point. Thus, with unity as the base, instead of "100," it is proposed to denote the former by "per unit" system, instead of "percentage" system.*

*Turning to the results of the paper, expressions are derived for the short-circuit currents in the armature and field, for voltage induced in the open phase, and for voltages across external reactances in the armature and field circuits. Comparison of calculated and test curves for these quantities are shown in Figs. 5 to 8, for a 7000-kv-a. 375 rev. per min. salient pole alternator, and in Figs. 11 to 25 for a 20-hp. 1800-rev. per min. induction machine (cylindrical rotor). These show satisfactory agreement.*

*The form of the results is interesting and instructive. The short-circuit currents are expressed, as in equation* (9), *as the sum of two series, one of odd, the other of even, harmonics, in which the magnitudes of the harmonics, in ascending order, are in geometric ratio. The value of that ratio is*

$$b = \frac{\sqrt{x_Q'} - \sqrt{x_D'}}{\sqrt{x_Q'} + \sqrt{x_D'}}$$

*where* $x_D$ *and* $x_Q$ *are transient reactances in the direct and quadrature axes.*

*The effect of salient poles in reducing the relative magnitude of the harmonics with respect to the fundamental in the short-circuit current is clearly shown by the equations. This is important both in connection with the calculation of mechanical forces, and of the voltage induced in the open phase during single-phase short circuit. It is shown that although this voltage may be 15 or 20 times normal in a laminated, cylindrical rotor machine without amortisseur circuits, it may be only 2 to 4 times normal in a salient pole machine. An amortisseur winding greatly reduces it in either case.*

*The fundamental component of this voltage across the open phase is shown to be approximately equal to (1 + b) times the voltage before short circuit.*

*The mathematical work and definitions are in Appendixes as follows:*

*A Summary of equations.*
*B Armature current.*
*C Field current.*
*D Voltage across external reactance in armature circuit.*
*E Voltage across external reactance in field circuit.*
*F Voltage across the open phase.*
*G Variation of armature inductance with position.*
*H Decrement factors.*
*I Reactances, definitions, and relations.*

## HISTORICAL

At the White Sulphur Springs Convention in 1926 the authors presented the first of a series of papers covering their investigations of the Synchronous Machines. Part I was an extension of fundamental theory; Part II, a treatment of torque-angle characteristics under steady state conditions; and Part III, presented at the 1927 Winter Convention, a study of torque-angle characteristics under transient conditions. In the present paper, an analysis is made of single-phase short circuits. In the future, the treatments of other characteristics, including polyphase short circuits and the torque existing under short-circuit conditions, may be given.

Certain special cases of short circuits have been treated previously. Following the early work by Steinmetz[1] and Berg, Boucherot[2] presented his classical paper in 1912, dealing with alternators of the laminated, cylindrical rotor type, with and without amortisseur windings. In 1915 Diamant[4] reviewed the work of Berg and Boucherot, and, among other mathematical extensions, gave expressions for the envelope of the short-circuit current. In 1918 he presented an analysis of sustained short circuits, dealing principally with the nature of flux distribution under that condition. In the same year[9a] one of the authors proposed the use of the *Constant Linkage Theorem* in dealing with short circuits, and in 1921[9b] and 1923[9c] illustrated its use. Also in 1923 Franklin[5] applied this method to a large number of cases of single-phase and three-phase short circuits. Working from the same fundamental premises, Laffoon[7] solved additional cases in 1924. The

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*Both of the General Electric Co.

1. For references see bibliography.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., February 13-17, 1928.*

following year Karapetoff[6] analyzed, in the main, the same cases as those of Franklin and Laffoon; but he started from a somewhat different theoretical basis, *i. e.*, from Kirchoff's Laws. But he, like Franklin and Laffoon, neglected resistance, which made the fundamental premises the same—since the Constant Linkage Theorem is merely a corollary of Kirchoff's Second Law, for the special case of negligible resistance. That is, his equations involved voltages, instead of magnetic linkages, and were therefore the first derivatives of the corresponding equations in Franklin's work. Involving the same assumptions regarding the circuits, the results naturally also agreed. In 1923, Lyon[13] outlined a method according to which "certain low-frequency transient conditions in electric machinery may be analyzed by a vector method." From the vector point of view, first proposed by Dreyfus[14, 15, 16] in 1912, the transient voltage or current may be represented by a series of vectors which shrink exponentially as they rotate. The thorough, mathematical treatments of cylindrical rotor machines both by Shimidzu and Ito[8] and by Biermanns,[3] in which the effect of resistance is approximately taken into account, are especially noteworthy. All of the foregoing investigations have dealt with cylindrical rotor machines; and, granting the simplifying assumptions which have appeared to be practically necessary, such as those made by Shimidzu and Ito, and Biermanns, relating to resistance and saturation, it may be said that a practical solution of short circuits for the cylindrical rotor type has been attained.*

## SCOPE

These previous analyses, however, have not solved the important case of salient pole machines. The present paper treats the general case, including both types. Proceeding from the same basic point of view from which the authors' previous work on Synchronous Machines[9d,9c] has been developed, the present treatment takes up single-phase short circuits and partial short circuits, *i. e.*, with external reactance in the armature and field circuits, developing expressions for armature current, field current, armature voltage across the open phases, voltage across reactance in the armature circuit, and the voltage across reactance in the field circuit. These expressions apply not only to salient pole machines, but also to the cylindrical rotor type, since under the present theory, the latter type merely becomes a special case of the former. Thus, the scope includes the development of expressions, applicable alike to salient poles and cylindrical rotors, for the voltage and current phenomena under single-phase short circuit.

Although the single-phase phenomena of *three-phase* machines only are considered here, the theory is, of course, applicable also to two-phase machines.

## DISCUSSION OF THEORY

The four basic concepts underlying the improvement in theory, both as applied here and in the authors' previous work, are: (1) characterization of the machine by four reactance coefficients, two corresponding to the main pole axis, *i. e., direct axis*, and two to the interpolar axis, *i. e., quadrature axis*. These are $x_D$, $x_D'$, $x_Q$, $x_Q'$. (See notation.) Thus the theory has been referred to, more or less aptly, as the "Four-Constant Theory.†

2. Resolution of flux and m. m. f. waves traveling with respect to the rotor into stationary, pulsating components in line with the *direct* and *quadrature* axes. The theory involves also, of course, the usual Blondel resolution of the *stationary* fundamental waves.

3. That the variable component of armature inductance varies between the *direct* axis value and the *quadrature* axis value as a second harmonic function of the electrical space angle. This applies to all variable components of inductance which, with armature current of fundamental frequency, produce fundamental voltage.

The general aspects of this premise should be carefully considered. In a salient pole machine, if the axis of the armature fundamental m. m. f. is not in line with either the pole axis or the interpolar axis, the resulting fundamental flux wave, of course, will not be in space phase with the m. m. f. wave; and therefore calculations involving the total waves would be very complicated. *By symmetry*, the flux wave will be in space phase with the m. m. f. wave producing it, if the latter is in line with either of these axes. The purpose of resolving the fundamental wave of m. m. f. along these two particular axes is thus to obtain component flux waves in space phase with the respective m. m. f. components producing them.

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*After submitting the present manuscript, a copy of S. Bekku's treatment of "Sudden Short Circuit of Alternator," Bibliography 12, has been received. This treats the case of the cylindrical rotor machine with a three-phase winding on the rotor, each rotor circuit being closed either directly or through the exciter. He employs "Heaviside" in the mathematical work.

†There are, of course, more than four. The four constants which characterize the machine under single-phase operation are not the same as the four which characterize it under polyphase operation. They are, however, of the same general nature, thus corresponding each to each, the chief difference being due to the mutual inductance between phases. Nor are the four constants the same for a line-to-neutral, as for a line-to-line, short circuit. Thus, there are twelve constants in this particular connection, and even some of these may be split up under special conditions; for instance, where saturation exists, or where there are short-circuited windings on the rotor in addition to the main field winding, etc. Moreover, in certain network calculations, it is desirable to use an additional constant, namely, the *zero phase-sequence reactance*. The *positive phase* and *negative phase* values are also used in the latter connection, but these are expressed in terms of the "four constants." And, if one should include also the calculation of all the possible phenomena due to harmonics, the number of necessary constants could be extended almost indefinitely. Thus while it is correct to say that the machine, under single-phase or polyphase operation, is characterized under the premises of this paper by four constants, there are, all told, many more than four values of reactance to be considered in general.

Now it is a mere incident of machine design that there is symmetry about the two axes mentioned, and that these axes happen to be 90 electrical degrees apart. But these facts underly the possibility of expressing the variation of armature inductance as a simple second harmonic, as in equation (3). For derivation of this, see Appendix G.

Such a variation is shown to apply not only in the case where the field winding is open circuited, *i. e.*, to the case of pure reluctance symmetry of the rotor magnetic circuit, but also to the case of artificial reluctance symmetry as produced by short-circuited rotor windings, such as the field winding. A short-circuited secondary on the rotor merely increases the reluctance of the path of the armature flux; and in machines as ordinarily constructed, the artificial reluctance symmetry is about the same two axes as when the secondary windings are open-circuited, since the axes of the latter windings coincide with the direct and quadrature axes. See Fig. 1.

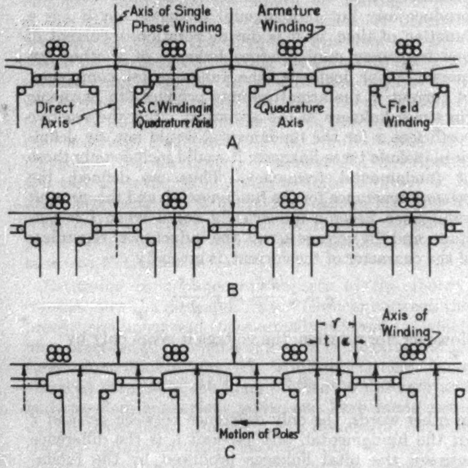

Fig. 1

There is also a relatively small component of *armature leakage inductance*, which varies as a second harmonic. Although this component is due to space harmonics of flux, it nevertheless produces a reactive voltage of the same frequency as the armature current. This has been considered by Karapetoff[6a] and Arnold,[11] its significance is fully discussed in *Synchronous Machines*, —*I*,[9d] and its magnitude is given by Alger.†

Thus, considering the variable components of inductance, it is permissible, under the premises, to regard the variation as a second harmonic of the electrical space angle, regardless of whether the variation is produced by the shape of the iron magnetic circuit, by short-circuited secondary windings on the rotor, or by both; and regardless of whether the variation affects the fundamental or the harmonic flux waves, so long as the reactive voltages produced by such waves are of fundamental frequency. Fig. 2 shows the variation of the transient inductance of a 20-hp. machine, on which many of the tests described herein were taken. Curve *A* was taken under the condition of no saturation, and is practically a sine wave of double frequency, whereas curve *B* was taken under the condition of partial saturation, and departs considerably from a sine wave—thus containing significant even harmonics. Fig. 3 shows the same curve for a four-pole, 15-k-va., 1800-rev. per min. salient-pole machine without saturation. Fig. 4 shows the curve for a 7000-k-va. machine. This

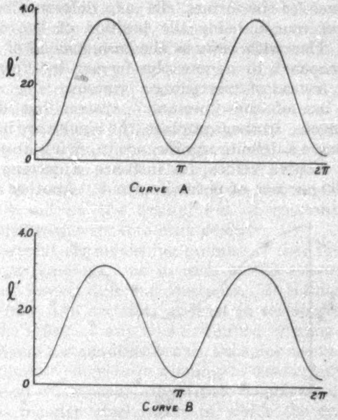

Fig. 2—Variation in Transient Inductance, 20-Hp. Machine

Curve A—No saturation
Curve B—With saturation

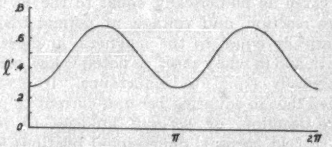

Fig. 3—Variation in Transient Inductance—4-Pole, 15-Kv-a., 1800-Rev. per Min., Salient-Pole Machine

was obtained from an oscillographic record taken in connection with the "slip method."‡

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†"Calculation of Reactance of Synchronous Machines," by P. A. Alger, p. 493.

4. The complete use of a fractional system of notation throughout the equations, thus expressing each quantity as a *decimal* fraction of some definite, convenient value, such as "normal" value. This is, of course, an outgrowth of the familiar practise of expressing such quantities as a percentage of normal value, but the latter involves carrying along the "100" in calculations, which is both cumbersome and conducive to numerical error. Experience has established a very definite preference for the former, the only difference between them, of course, being the position of the decimal point. Thus with *unity* as the base, instead of "100," it is proposed to denote the former by "per-unit" system, instead of "percentage" system.

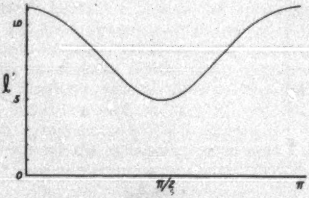

FIG. 4—VARIATION IN TRANSIENT INDUCTANCE—7000-KV-A. MACHINE

The use of the "per-unit" system has distinct advantages. In the first place, the results are in forms which have a definite significance in giving at once an idea of relative values; for instance, a current of 0.5 means 50 per cent of normal current. Another advantage is that cumbersome conversion factors are thus eliminated. For instance, as *per-unit* quantities, current is taken as numerically equal to the m. m. f. of armature reaction, and voltage, at normal frequency, as numerically equal to the magnetic linkages which produce it, and in many cases, as noted below, reactance as numerically equal to inductance. It should be mentioned that in equating *per-unit* current to *per-unit* armature reaction, or *per-unit* linkages to *per-unit* voltage or field current, dimensional relations are not disturbed, because all values are ratios; *i. e.*, all values are numerics. Conversion factors thus become unnecessary.

At some risk of confusion, attention is also called to the fact that, according to the definitions, reactance and inductance, *as per-unit quantities*, become identical numerically in many special cases where the reactance is based on fundamental frequency. Reactance is still reactance, and inductance is still inductance; but with each expressed as a ratio, *i. e.*, as a numeric, they become, by definition, numerically equal under the special condition referred to. The definitions are: *per-unit inductance for the nth harmonic is the ratio of the nth harmonic linkages, produced by an nth harmonic current of normal value, to normal linkages.* And, *per-unit reactances for the nth harmonic is the ratio of the nth harmonic reactive voltage due to an nth harmonic current of normal value, to normal voltage.* Thus, if $l$ is the circuit inductance, $i_n\, l$ gives the *per-unit* linkages due to the $n$th harmonic current $i_n$, and $i_n\, x_n$ gives the corresponding *per-unit* reactive voltage. For the fundamental component of current $i$,

$$i\,x = i\,l$$

provided all of the linkages due to $i$ produce voltage of fundamental frequency; and if so, $x = l$. But this is not always so. If the inductance $l$ is constant, the linkages must be proportional to the current (under the premises), and the fundamental current could not produce any but fundamental linkages; but if $l$ is a function of time, as it is during rotation, a current of one frequency may produce linkages of another frequency. For instance, the fundamental component of current in the armature may produce 5th harmonic (in time) linkages in the armature. But the reactive coefficient $x$ for the fundamental would not, by definition, include these linkages; it would include only those of fundamental frequency. Thus, as defined, the *per-unit* reactance for the fundamental, and the *per-unit* inductance become numerically equal when $l$ is constant, and the voltage across the inductance, regardless of the character of the current, is given by

$$e = l\,\frac{d\,i}{d\,t} = x\,\frac{d\,i}{d\,t}$$

However, for rotation, the voltage is given only by

$$e = \frac{d}{d\,t}\,(l\,i)$$

In other words, the only difference between *per-unit* $x$ for the fundamental, and *per-unit* $l$, is the difference between the total linkages produced by the fundamental current $i$, and that component of the total which is of the same frequency as $i$. Hence when there is no difference, that is, when the linkages are at all instants proportional to the component of current under consideration, $x$ and $l$ may be taken as numerically identical.

So, considering the system of notation as a whole, although it may possibly be a bit confusing at first, it is nevertheless sound, has very great advantages in simplifying equations, and in giving an added significance to the results, and is time-tried; *i. e.*, has proved its value over years of day-to-day practical use in the solution of complicated problems.

The four basic concepts outlined in the foregoing paragraphs, afford the basis for symmetrical, relatively simple, and very interesting expressions for the voltage and currents under single-phase operation. It has been possible in this way to take into account, without undue mathematical complication, the *predominating factors* of the problem, and therefore to obtain a very satisfactory agreement between calculated and test results, as may be seen by reference to Figs. 11 and others which follow.

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‡See R. H. Park & B. L. Robertson, p. 514.

These extensions in theory have required not only additional characteristic machine constants, as already mentioned in a footnote, but also have made it necessary, in order to avoid confusion and misunderstanding, to classify and more carefully define them. In the early days, a synchronous machine had *a* reactance; now it has many. Moreover, our ideas about some of the well established terms, for instance, *armature leakage reactance*, and *field leakage reactance*, have needed some revision. As a rough illustration in connection with the general situation; in running a polygonal boundary, an error in the length or bearing of one of the sides is not so apparent, unless it becomes necessary to "close" the polygon. The error is merely passed on the next side, letting the end whip about as occasion may require. In synchronous machines, it was formerly necessary to "run" only one or two sides; now, with the necessity of calculating practically all of the electrical characteristics, we must "close the polygon." So, an orderly classification, description and careful definition of terms is quite in order, as is also the presentation of methods of calculating some of these factors. The former is given in a companion paper by R. H. Park and B. L. Robertson; and the latter, by P. L. Alger.

Returning to the general aspects of the theory, consider now the distinguishing differences between the present treatment and those already referred to, which have preceded it. Boucherot's work is the outstanding early contribution on the subject. Others have attacked essentially the same problem in different and perhaps more convenient ways, and have made noteworthy extensions. But they, like Boucherot, have all treated *cylindrical rotor machines only*, whereas the present investigation has dealt with the general case including salient pole machines, the cylindrical rotor type thus becoming merely a limiting case. It may be of interest, therefore, to draw some specific comparison relating to the differences in fundamental premises, and hence also in the resulting equations.

There are two fundamental assumptions which distinguish the general treatment from that of cylindrical rotors. The first relates to the character of the *total* armature self-inductance; Boucherot's $L_1$, the authors' $\mathcal{L}_D$ and $\mathcal{L}_Q$. In the cylindrical rotor theory, this inductance is assumed to be constant with respect to position—in other words, that the air-gap is uniform; in the present theory, it is assumed to be variable,* as it actually is in salient pole machines. In the limit, when there is no variation, that is, when $\mathcal{L}_D$ and $\mathcal{L}_Q$ are equal, the equations then apply to cylindrical rotor machines.

What difference does it make in the results if that inductance is assumed to be variable? It makes a large difference in the relative magnitudes of the fundamental and harmonics, and thus also in the ratio of the amplitude of the fundamental to the peak value, both in the short circuit current, and in the open phase voltage. One important result of the theory is that the *peak value* is the same for salient poles as for cylindrical rotors, when the transient reactance, direct axis, is the same. Thus equations (**18b**) and (**19b**) show, as indicated graphically in Fig. 9, that the peak is independent of $x_Q'$. The magnitudes of the harmonics and of the fundamental are very important, both in determining mechanical stresses and angular vibrations, and also in determining the voltage in the open phase and across external reactance. These are greatly affected by salient poles, and can be predetermined with practical accuracy from the present theory. But they obviously cannot be correctly calculated from cylindrical rotor theory based on the assumption of constant total inductance with respect to rotor position.

The second distinguishing premise is that there are two rotor windings, one in each of the conventional axes, and having different constants. It is thus possible to take into account, at least in an approximate way, the effect of any short-circuited winding which may exist in the quadrature axis, such, for instance, as a non-uniform squirrel-cage winding, as used in laminated cylindrical rotors, or in salient-pole machines, and also such as massive steel rotors in which the transient reactances $x_D'$ and $x_Q'$ are different. And if there are actually only two distinct rotor circuits in the two axes, even though they have different constants, the theory is completely applicable. Moreover, for a special case of cylindrical rotor in which there are two rotor windings at 90 deg., *i. e.*, one in each axis, and also in which $x_D' > x_Q'$, the characteristics can not be calculated, so far as the authors are aware, by the previous cylindrical theory. But they are easily calculated and analyzed by the present theory. This is illustrated by reference to Figs. 13, 14, and 15, which apply to such a case. These are explained under "Results." Thus, the second distinguishing assumption broadens the application of the theory over the previous theory, even in the case of cylindrical rotors.

### ASSUMPTIONS

1. *Negligible saturation.* This is, of course, not true practically. However, as mentioned in *Synchronous Machines—III*, this does not prevent the use of the results in cases where saturation is present, by judicious shading of the constants, or by shading the calculated results with respect to the degree and distribution of the saturation; remembering, however, that the method thus applied is an approximation.

2. *The open-circuit voltage is a sine wave.* This is

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*The total variable component comprises not only the variable term of the inductance of armature reaction, but also the small variable term of armature leakage inductance.

practically true of most modern alternators. The combined effect of coil pitch, distribution of the winding, $Y$-connection, and perhaps "fractional slot" winding, practically eliminates all harmonics in the voltage wave. So this assumption is reasonably correct for most synchronous machines. The only significant practical departure might be in the case of the line-to-neutral voltage of a machine with a relatively small number of full pitch coils per pole, in which case there might be a significant third, and possibly other odd harmonics.

3. *The machine has a short-circuited rotor winding in the quadrature axis, as well as the main field winding in the direct axis.* (See Fig. 1.)

4. *Resistance of the armature and field circuits is neglected in calculating the magnitude of the initial short-circuit current; and the armature resistance, in calculating the magnitude of the sustained current. But both resistances are taken into account in the decrements.* The effect of resistance in the impedance is usually insignificant, but its effect on the decrement is, of course, very pronounced. Indeed, there would be no decrement without resistance.

5. *The machine is short-circuited at no-load.* A suggested extension of the theory is to take into account the relatively small effect of load current.

### FUNDAMENTAL EQUATIONS

The general plan of attack and the general considerations leading up to the fundamental equations will be discussed here, and the final equations will be derived in the Appendix.

Superposition is used in obtaining the initial values of armature and field current. The plan is first to find a general expression for the magnetic linkages of the armature winding, due to any transient armature current, and with no field current except that induced by the armature current; and then to determine the armature linkages due to any other current in the field winding, and superpose these to find the resultant value of armature linkages. Under short circuit, and neglecting resistance, the latter value of linkages must be equal to the known value existing at the instant of short circuit.* These relations are sufficient to solve for the *initial* armature current $i$.

The *initial* value of field current is obtained by adding the component induced by the armature winding, to the steady value existing the instant before short circuit.

There are certain components of the *initial* current which are known to be transient. These, as a function of time, are obtained by multiplying the individual transient components by the appropriate decrement factor.

The sustained values, of course, comprise those components which exist after the transients have disappeared, and are thus obtained by setting the transient terms equal to zero.

The decrement factors are obtained by an approximation. It seems to be well nigh hopeless, as a practical matter, to take into account rigorously the armature and field resistances in the general case, but it happens fortunately that it is possible to obtain results which are sufficiently accurate for any practical purpose, by making simplifying assumptions.

Before stating these specifically, the physics of the transient currents will be briefly considered. When the armature winding is short-circuited, the magnetic flux linked with the closed field circuit can not change significantly in the first moment, yet, since it can not now enter the short-circuited armature winding, it is forced by the demagnetizing action of the armature currents, to pass through paths (the leakage paths) of greater reluctance; that is, the short-circuited armature is equivalent to an increased magnetic reluctance. Hence, an additional current must appear in the field circuit in order to sustain the flux in those new paths, and this spontaneous additional direct current, being unsupported by the exciter voltage, is, of course, transient in character; that is, the voltage which supports it through the resistance of the field circuit, is generated by the decay of the flux through that circuit. Considered thus, the problem of determining the transient becomes practically identical with that of determining it for the simple inductive circuit, namely, to obtain the simple decrement factor $\frac{r}{L}$, in which $r$ is the resistance of the circuit through which the transient flux is decaying, and $L$ is the total circuit inductance defined by the ratio of the total linkages of the circuit, to the current required to sustain them, this decrement factor being applied to the transient component of current. This general view of decrements was presented by one of the authors[9a] in 1918, and is essentially the same as that used by Biermanns.

How does armature resistance affect the field decrement factor? From the limit of zero armature resistance, on the one hand, for which *all* flux linkages are forced into the high reluctance leakage paths, to infinite resistance on the other, that is open circuit, under which condition none of the flux is forced out of the normal magnetic path of relatively low reluctance, there are, as far as the field transient is concerned, all possible intervening values of effective reluctance and corresponding inductance. Thus, the effect of armature resistance on the field transient may be taken into account in the field decrement factor by appropriate modification of the inductance. This is done when that resistance is large enough to affect significantly the value of the *direct axis* component of armature current. It is rarely necessary to do this, but when it is, it is a much easier task than to attempt a rigorous solution, which, to the author's knowledge, has been obtained only in the special and limited cases treated by Biermanns,[3] Shimidzu and Ito,[8] and Bekku.[12]

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*Constant Linkage Theorem. See Bibliography 9c.

The same general argument may be applied to the effect of field resistance upon the armature decrement factor, that is, with respect to the transient flux linkages which are "trapped" in the short circuit armature winding.

Thus, the approximation is made that, unless the armature resistance is large enough to become significant in the impedance, *i. e.*, large enough to affect the demagnetizing current in the direct axis, it is neglected in the field decrement factor; and when it is taken into account, this is done by an appropriate modification of the inductance. And under similar limitations, the field resistance is neglected in the armature decrement factor.

The field decrement factor is applied to the induced direct component of current in the field, and to all other phenomena which depend on that current in direct proportion, such as the transient alternating component of current in the armature, and the armature circuit voltages which are due to the latter. And likewise the armature decrement factor is applied to the d-c. component in the armature and to all other phenomena which thus depend upon it, such as the transient a-c. component in the field circuit, and the voltages which are due to the latter. For the derivation of decrement factors see Appendix H.

The armature decrement factor is,

$$\sigma_a = \frac{r}{\sqrt{x_D'\,x_Q'}} \tag{1}$$

and the field decrement,

$$\sigma_f = \frac{x_D + \sqrt{x_D'\,x_Q'}}{x_D' + \sqrt{x_D'\,x_Q'}}\,\sigma_0 \tag{2}$$

where $\sigma_0$ is the decrement factor of the field corresponding to *total* field self-inductance.

Another item for consideration is the voltage across an external inductance in either the armature or field circuit. This is found by differentiating the particular current with respect to time, and taking the product of this by the external inductance coefficient. These voltages are derived in Appendixes D and E.

Still another is the voltage across the open phase of a three-phase machine during short circuit of one of the phases. This is determined by first obtaining an expression for the linkages with the open phase in question, and differentiating this with respect to time. This is given in Appendix F.

Turning now to the details of the fundamental equations, refer to Fig. 1A. If a transient current $i$ is caused to flow in the armature winding in the position shown, that is, with the direct axis and the armature winding axis coinciding, a current will, of course, appear in the field winding which is short-circuited either at the terminals or through an external inductance. Thus, fluxes will be produced in the leakage paths of both the armature winding and the short-circuited field winding. Corresponding to these fluxes there will be a *direct static transient* inductance $\mathfrak{L}_D'$ and corresponding reactance $x_D'$; similarly, when the quadrature axis is lined up with the axis of the armature winding, as in 1B, there will be a *quadrature static transient* inductance $l_Q$ and corresponding reactance $x_Q'$. For any other position, as in 1C, the inductance will vary, as previously shown, between $x_D'$ and $x_Q'$ as a second harmonic function of the angle $\gamma$ between the armature winding axis and the direct axis. Thus

$$l' = \frac{1}{2}\left[\,(l_D' + l_Q') + (l_D' - l_Q')\cos 2\,\gamma\,\right]$$

Or, since $x_D'$ and $x_Q'$ are "static" values of *per-unit* reactance, they may be taken, as already explained, as equal to the corresponding inductance. Hence,

$$l' = \frac{1}{2}\left[(x_D' + x_Q') + (x_D' - x_Q')\cos 2\,\gamma\right] \tag{3}$$

Let the transient armature current be due to a single-phase short circuit occurring during rotation at uniform speed, and at the instant when the direct axis is displaced from the armature axis by the angle $\alpha$. Counting time from this instant, the angle $\gamma$ becomes a function of time.

$$\gamma = t + \alpha \tag{4}$$

Therefore, any transient current, $i$, which exists at any time $t$, will produce the following flux linkages with the armature winding,

$$\psi_i = l'\,i = \frac{1}{2}\,i\left[(x_D' + x_Q') + (x_D' - x_Q')\cos 2\,(t + \alpha)\right] \tag{5}$$

The current existing in the field winding before short circuit, would produce in the open circuited armature winding at any time $t$ the alternating mutual flux linkages,

$$\psi_m = k\,e_0 \cos\,(t + \alpha) \tag{6}$$

where $e_0$ represents the peak voltage, line-to-neutral, generated before short circuit, and therefore also *the flux linkages;* and since on open circuit, terminal voltage is also nominal voltage, $e_0$ also represents the corresponding field current. $k$ is a factor whose value depends upon the nature of the short circuit, *i. e.*, whether line-to-neutral or line-to-line. Thus, $k = 1.0$ for line-to-neutral, and 1.73 for line-to-line.

The sum of (5) and (6), must equal the linkages existing at the instant before short circuit, namely,

$$\psi_m = k\,e_0 \cos\alpha \tag{7}$$

The above relations determine the total armature current, as derived in Appendix B.

The total field currents are given by

$$\left.\begin{aligned} &I_d = e_d = e_0 + \Delta\,e_d \\ \text{and}\quad &I_q = e_q = \Delta\,e_q \end{aligned}\right\} \tag{8}$$

where $e_d$ represents *direct* nominal voltage, and therefore also the total field current in the direct axis winding, and $\Delta e_d$ the increment induced by the transient armature current. Similarly, $\Delta e_q$ represents the increment induced in the *quadrature* axis winding. It is assumed that the only quadrature component is the induced current. The field current is derived in Appendix C.

## RESULTS

The foremost result is the method of analysis which makes possible, in a practical way, the calculation of transient phenomena in any synchronous machine, regardless of whether it is of the salient pole or the cylindrical rotor type. The equations thus derived have made it possible to calculate complicated transient characteristics which check, in minute details, with the oscillographic records of tests; and these equations have revealed a number of important and very interesting facts relating to the form of the current waves, the resulting possibility of relatively simple analysis of the waves, and the induced voltage in the open phase during single-phase short circuit. A summary of equations is given in Appendix A.

Referring to the short-circuit current waves, the current is expressed as the sum of two harmonic series, one of odd, the other of even, harmonics; and the *magnitudes of the harmonics in each series, in ascending order*, are in *geometric ratio*. Thus, the single-phase short-circuit current of the armature is

$$\begin{aligned} i = & \frac{k\, e_0 \cos\alpha}{\sqrt{x_D'\, x_Q'}} [1 + 2\,b \cos 2\,(t+\alpha) \\ & + 2\,b^2 \cos 4\,(t+\alpha) + 2\,b^3 \cos 6\,(t+\alpha) + \ldots .] \\ & - \frac{2\,k\,e_0}{x_D' + \sqrt{x_D'\, x_Q'}} [\cos\,(t+\alpha) + b \cos 3\,(t+\alpha) \\ & + b^2 \cos 5\,(t+\alpha) + b^3 \cos 7\,(t+\alpha) + \ldots] \end{aligned} \qquad (\mathbf{9})$$

The geometric ratio $b$ is given by

$$b = \frac{\sqrt{x_Q'} - \sqrt{x_D'}}{\sqrt{x_Q'} + \sqrt{x_D'}}$$

where $x_Q'$ is the transient reactance in the quadrature axis, and $x_D'$ the corresponding quantity in the direct axis.

For instance, a 7000-k-va., 375-rev. per min., 25-cycle, 2200-volt salient-pole machine of usual construction has the following constants.*

$x_D' = 0.4$
$x_Q' = 1.0$
$b \cong 0.23$

In this machine, the 3rd harmonic in the short-circuit current would be 23 per cent of the fundamental, the 5th 23 per cent of the 3rd, the 7th 23 per cent of the 5th, and so on. Likewise for the even harmonics. The total wave, both calculated and tested, is shown in Fig. 5 for armature current, and Fig. 6 for field current.

As an extreme case,

$x_D' = 0.21$
$x_Q' = 3.77$
$b = 0.618$

These constants apply to an actual induction machine with a coil wound secondary.† The armature is three-phase, the rotor two-phase; the latter, in this particular case, being connected two phases in series with direct-current excitation. The machine is rated 20-hp., 1800-rev. per min., 60-cycle, 110-volt. For convenience, the *per-unit* quantities are based on 10-kv-a., three-phase, 57.7-volt line-to-neutral.

With the rotor winding thus connected, the harmonics are relatively 2.67 times as large as in the previous case of the 7000-kv-a. salient-pole machine. The waves of current, both calculated and test, are shown in Figs. 11-13, for the armature current, Figs. 16-18 for the field current.

It is interesting to note that if $b = 0$, that is if $x_D' = x_Q'$, all harmonics disappear, and the current wave changes from the peaked wave in Fig. 13 to approximately a sine wave, as in Fig. 14. The values of $x_D'$ and $x_Q'$ were made practically equal by short circuiting one of the two rotor phases, and exciting the other, keeping the external impedance of the latter as low as possible.

Going a step further, $x_D'$ can be made greater than $x_Q'$ by placing external inductance in the field winding which is excited, *i. e.*, the direct axis winding. In this case the sign of the harmonics is reversed, *i. e.*, $b$ becomes negative, thus giving a dip in the wave. This is shown in Fig. 15.

Referring again to equation (**9**), it is interesting to consider how limiting values of $b$ modify the shape of the current waves. The first series, *i. e.*, even harmonics, has the general form shown in Fig. 9A. The second series has the general form shown in Fig. 9B. The total current, the sum of the two series, has the general form of Fig. 9C.

Now if $x_D'$ and $x_Q'$ are equal, $b$ becomes zero, and all

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*It should be remembered that these constants represent the *static transient linkages* (or, at normal frequency, the corresponding reactive voltage) as a fraction of normal linkages, *line-to neutral*, (or, at normal frequency, the *line-to-neutral* normal voltage). The values given look high compared with the usual three-phase values, because they are *line-to-line* constants. If the line-to-line voltages were taken as the per-unit base, instead of line-to-neutral, the values would be divided by $\sqrt{3}$. Also, the corresponding line-to-neutral, three-phase values would be just one-half the values given. See companion paper by Park and Robertson regarding the relations between three-phase and single-phase constants.

†This machine was chosen with the two points in mind; one was that our premises should be closely approximated; the other, that it was desirable, in the interest of an exacting test of the theory, to employ extreme limits in reactance coefficients thus involving harmonics of large magnitude, which harmonics, nevertheless, would be capable of control by different connections of the windings, and by variation of constants in the external circuits.

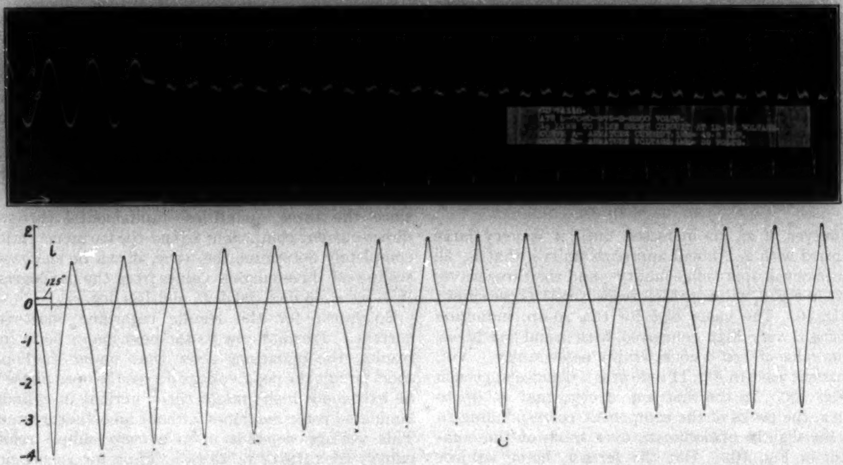

FIG. 5—SINGLE-PHASE LINE TO LINE SHORT CIRCUIT AT $\alpha = 55$ DEG., 7000-KV-A. MACHINE

A—Test curve of armature current

B—Test curve of open-phase voltage

C—Calculated curve of armature current with test points indicating the peaks

Equation:—

$$i = \frac{0.59}{1.4 - 0.6 \cos (2t + 110°)} \epsilon^{-0.01168t} - \frac{0.358 \cos (t + 55°)}{1.4 - 0.6 \cos (2t + 110°)} - \frac{0.641 \cos (t + 55°)}{1.4 - 0.6 \cos (2t + 110°)} \epsilon^{-0.00272t}$$

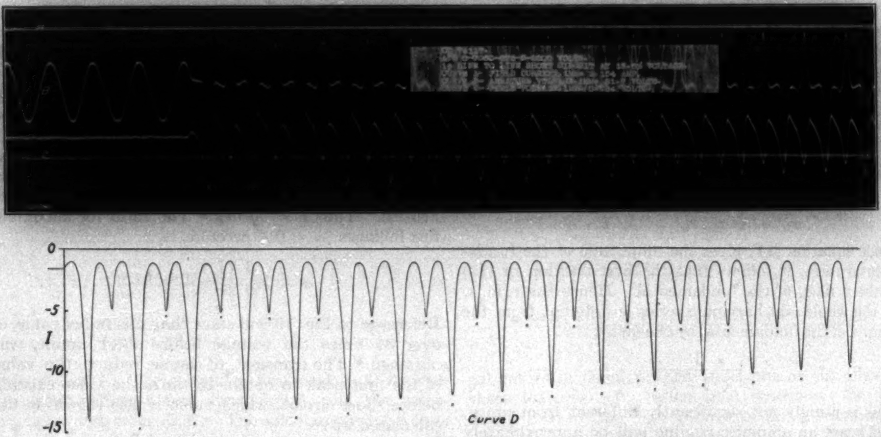

FIG. 6—SINGLE-PHASE LINE-TO-LINE SHORT CIRCUIT AT $\alpha = 55$ DEG., 7000-KV-A. MACHINE

A—Test curve of field current

B—Test curve of open-phase voltage

C—Test curve of voltage across external reactor in field circuit

D—Calculated curve of field current with test points indicating the peaks

Equation:—

$$I = -\frac{0.364 \cos (t + 55°)}{1.4 - 0.6 \cos (2t + 110°)} \epsilon^{-0.01168t} + \frac{0.624 [3.24 + 1.24 \cos (2t + 110°)]}{1.4 - 0.6 \cos (2t + 110°)} + \frac{1.109 [3.24 + 1.24 \cos (2t + 110°)]}{1.4 - 0.6 \cos (2t + 110°)} \epsilon^{-0.00272t}$$

harmonics vanish, as already indicated. Taking $\alpha = 0$, the first series then reduces to only a d-c. component of an amplitude

$$i_0 = \frac{k\, e_0}{\sqrt{x_D'\, x_Q'}} \tag{10}$$

And the second series then contains only a fundamental term of amplitude

$$i_1 = \frac{2\, k\, e_0}{x_D' + \sqrt{x_D'\, x_Q'}} \tag{11}$$

However, if $x_Q'$ is increased until it is very large compared with $x_D'$, $b$ will approach unity—that is, all harmonics will approach equality—and the three waves shown in Fig. 9, will approach respectively those shown in Fig. 10. The value of $b$ for the 20-hp. induction machine is very high compared with usual machines, but its value of 0.62 is considerably below unity. Yet, the current wave in Fig. 11 indicates a definite approach to Fig. 10C. In the first four cycles, that is, up to $t = 8\,\pi$, the peaks of the component corresponding to Fig. 10A slightly predominate over those of the component in Fig. 10B. But the former, being subject to a more rapid decrement, become less after the fourth cycle, and the little *resultant* "tip" reverses direction. Note that the calculated wave in Fig. 11 checks the test perfectly in this detail.

Another interesting and useful feature of the expressions for short-circuit currents is that they open up new possibilities of analyzing the current waves. In addition to the relations shown in Fig. 9C and Fig. 10C, and the expression for the fundamental component of current in equation (**10**), it is shown in Appendix B that the r. m. s. value of the first series, *i. e.*, even harmonics, of equation (**9**), is

$$i = \frac{k\, e_0 \cos \alpha}{\sqrt{x_D'\, x_Q'}} \sqrt{\frac{1 + b^2}{1 - b^2}} \tag{12}$$

and of the odd harmonics

$$i_b = \frac{\sqrt{2}\, k\, e_0}{x_D' + \sqrt{x_D'\, x_Q'}} \; \frac{1}{\sqrt{1 - b^2}} \tag{13}$$

Since equation (**11**) gives the amplitude of the fundamental term, it follows that the first fraction in (**13**) is the r. m. s. of the fundamental. Hence the r. m. s. of the whole odd harmonic series is different from the r. m. s. of the fundamental by the factor

$$\frac{1}{\sqrt{1 - b^2}}$$

This is usually not significantly different from unity, and hence an ammeter reading will be approximately the fundamental. For instance, $b = 0.5$ would be an extremely high value for any commercial synchronous machine. The corresponding value of the factor is 1.15. However, a representative value of $b$ might be 0.2, for which the corresponding ratio is 1.02; that is, the ammeter would read 2 per cent more than the fundamental. Hence this might be a useful approximation.

Another possibility of convenient analysis of the oscillograph current wave is afforded by the fact that, with the harmonic ratio $b$, if one harmonic in each series is determined, all of them are known. The convenient relations exist that the peak value of the odd harmonic series is $1/(1 - b)$ times the peak value of the fundamental component, and the peak value of the even harmonic series is $(1 + b)/(1 - b)$ times the direct current component. It is shown in Appendix B that since the three quantities—fundamental current $i_1$, direct-current component $i_0$, and the harmonic ratio $b$—completely determine the wave, it can be analyzed by scaling off three current values from the oscillogram at $(t + \alpha) = 45$ deg., 90 deg., and 180 deg.

So much for the results regarding short-circuit current. Turning now to the next major point in the results, the equations show that under single-phase short circuit the peak voltage across the open phase may be extremely high; many times normal in cylindrical laminated rotor machines without amortisseur winding. This voltage depends upon a very simple relation, namely the ratio of $x_Q'$ to $x_D'$. Thus, for a short circuit at $\alpha = 0$—that is, at maximum flux enclosure or maximum flux linkages—the ratio of the voltage across the open phase after short circuit (initial value) to the peak voltage before short circuit is

$$\rho_o = \left( 2\, \frac{x_Q'}{x_D'} - 1 \right) \sin \beta \tag{14}$$

and for short circuit at zero flux linkages, *i. e.*, $\alpha = \pi/2$.

$$\rho\, \pi/2 = \frac{x_Q'}{x_D'} \sin \beta \tag{15}$$

where $\beta$ is the angle between the axis of the short-circuited winding, and the axis of the open-circuited winding considered.

Thus, as an extreme case, consider the 20-hp. machine. Here the short circuit was line-to-line, and the voltage recorded was across the open phase line-to-neutral. Thus $\beta = 90$ deg. The ratio for maximum flux linkages ($\alpha = 0$), therefore, is,

$$\rho = 2\, \frac{3.77}{0.21} - 1 = 34.9$$

Reference to Fig. 19 will show that this *initial* value, of over 34 times the voltage before short circuit, was obtained. The transient, of course, reduced the value of the first peak to obtain 28 times the value existing before short circuit, which value is also shown on the calculated wave.

When $x_D' = x_Q'$, the maximum voltage for the case considered is unity.

Turning to the test on the 7000-kv-a. salient-pole machine, the short circuit was line-to-line, and the open-phase voltage recorded was also line-to-line. Thus $\beta = 60$ deg., and from (**14**),

$$\rho = 3.46 \text{ for } \alpha = 0$$

and $$\rho = 2.16 \text{ for } \alpha = \pi/2$$

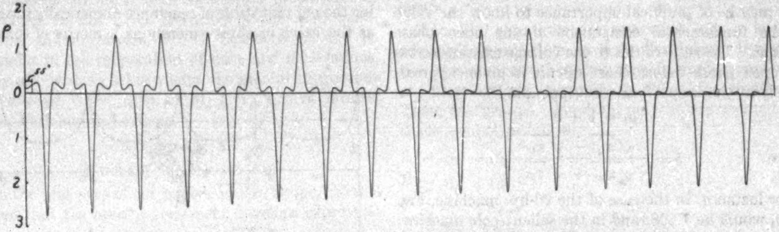

FIG. 7—CALCULATED CURVE OF TRANSIENT OPEN-PHASE VOLTAGE, SINGLE-PHASE. LINE-TO-LINE, SHORT CIRCUIT AT $\alpha = 55$ DEG., 7000-KV-A. MACHINE. (FOR TEST RESULTS REFER TO FIG. 5B.)

Equation:—

$$\begin{aligned} \epsilon = 2.38 & \left[ \frac{[0.35 - 0.3 \cos (2t + 170°)] \sin (2t + 110°)}{1.4 - 0.6 \cos (2t + 110°)^2} \right. \\ & \left. - \frac{1.194 \sin (2t + 170°)}{1.4 - 0.6 \cos (2t + 110°)} \right] \epsilon^{-0.01168t} + (1 + 1.77\, \epsilon^{-0.00272t}) \\ & \left\{ 0.624 \sin (t + 115°) + \frac{0.746 \sin (2t + 170) \cos (t + 55)}{1.4 - 0.6 \cos (2t + 110°)} \right. \\ & - 1.24 \frac{[0.35 - 0.3 \cos (2t + 170°)] \sin (t + 55°)}{1.4 - 0.6 \cos (2t + 110°)} \\ & \left. - \frac{1.49 [0.35 - 0.3 \cos (2t + 170°)] \sin (2t + 110°) \cos (t + 55°)}{[1.4 - 0.6 \cos (2t + 110°)]^2} \right\} \end{aligned}$$

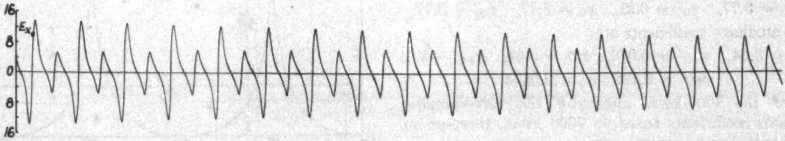

FIG. 8—TRANSIENT VOLTAGE ACROSS AN EXTERNAL REACTOR IN THE FIELD CIRCUIT, SINGLE-PHASE LINE-TO-LINE SHORT CIRCUIT AT $\alpha = 55$ DEG., 7000-KV-A. MACHINE. (FOR TEST RESULTS REFER TO FIG. 6C.)

Equation:—

$$\begin{aligned} \epsilon = & \left\{ \frac{0.0425 \cos (t + 55°) + 3.64 \sin (t + 55°)}{1.4 - 0.6 \cos (2t + 110°)} \right. \\ & \left. + \frac{4.37 \cos (t + 55°) \sin (2t + 110°)}{[1.4 - 0.6 \cos (2t + 110°)]^2} \right\} \epsilon^{-.01168t} \\ & - \left\{ \frac{1.55 \sin (2t + 110°)}{1.4 - 0.6 \cos (2t + 110°)} \right. \\ & \left. + \frac{0.75 \sin (2t + 110°) [3.24 + 1.24 \cos (2t + 110°)]}{[1.4 - 0.6 \cos (2t + 110°)]^2} \right\} \\ & - \left\{ \frac{2.75 \sin (2t + 110°)}{1.4 - 0.6 \cos (2t + 110°)} \right. \\ & \left. + \frac{1.33 \sin (2t + 110°) [3.24 + 1.24 \cos (2t + 110°)]}{[1.4 - 0.6 \cos (2t + 110°)]^2} \right\} \epsilon^{-0.00272t} \end{aligned}$$

These are limiting values. In the test, the short circuit occurred at $\alpha = 2.2$ (*i. e.*, about 125 deg.) and therefore the peak should fall between those indicated by the above values of $\rho$. Using $\alpha = 125$ deg. (or, for convenience, the corresponding value, 55 deg.) in the equation of Appendix F, the calculated wave Fig. 7 was obtained. The calculated first peak is 2.73 times the peak voltage before short circuit, and the corresponding test value, 2.97. The calculated value is thus less than the test by 8 per cent, which is a reasonable check, considering the probable error in scaling the angle from the oscillogram, and that due to the simplifying assumption made in Appendix F. And it will be noted that the shape of the curve checks satisfactorily. Thus, the voltage across the open phase during single-phase short circuit may rise to a peak value many times the value existing before short circuit. It varies almost directly with the ratio $x_Q'$ to $x_D'$. Hence, it would be extremely high—possibly 15 or 20 times normal voltage —on a cylindrical, laminated rotor machine without a squirrel-cage or metal wedges, serving the same purpose; but is practically no greater than normal when $x_Q' = x'_D$, as in a machine which has an amortisseur winding or massive steel rotor. Most of the cylindrical rotors in usual practise have one or the other of these features. In salient-pole machines, the tendency toward this high voltage is less, because $x_D'$ is relatively higher, and $x_Q'$, on account of salient poles, is relatively lower than in cylindrical rotor machines; but as shown in the foregoing actual illustration, the peak voltage, even in this case, may be from 2 to 3.5 times normal. A very important point to observe in this connection is that this high voltage across the open phase is due, not to high flux density, but rather to a high rate of change, and hence saturation would not limit it, unless by tending to equalize $x_D'$ and $x_Q'$.

Boucherot[2] called attention to the possibility of high voltage across the open phase, and to the favorable effect of an amortisseur winding in reducing it. The value of the present treatment in this connection is that the equations, in addition to being generally applicable, show the very significant extent to which salient poles reduce this voltage.

It may be of practical importance to know the value of the fundamental component of the open phase voltage. The ratio of this to the voltage existing across the open phase before short circuit is given approximately by the simple form (see Appendix F),

$$\rho_1 = 1 + b$$

where

$$b = \frac{\sqrt{x_Q'} - \sqrt{x_D'}}{\sqrt{x_Q'} + \sqrt{x_D'}}$$

For instance, in the case of the 20-hp. machine, Fig. 19, $\rho_1$ would be 1.628; and in the salient-pole machine, Fig. 7, for corresponding conditions, 1.23.

## COMPARISON OF CALCULATED AND TEST RESULTS

Calculations and tests were made on the two machines already referred to, namely, a 20-hp., 1800-rev. per min., 60-cycle, 110-volt induction machine, and a 7000-kv-a., 375-rev. per min., 25-cycle, 2200-volt salient-pole alternator. The four major *per-unit* coefficients (measured) for the 20-hp. machine, on the basis of 10 kv-a., three-phase, 57.7 volts line-to-neutral, are:

$$x_D = 3.77, \quad x_D' = 0.21, \quad x_Q = 3.77, \quad x_Q' = 3.77$$

The auxiliary coefficients are:

$$x_{AD} = 3.64, \quad x_{AD}' = 0.076, \quad x_{AQ} = 3.64, \quad x_{AQ}' = 3.64$$

$$\sigma_f = 0.132 \quad \sigma_a = 0.0474$$

For the 7000-kv-a. alternator the corresponding *per-unit* coefficients based on 7000 kv-a., three-phase, 1270 volts line-to-neutral, are:

$$x_D = 2.24, \quad x_D' = 0.40, \quad x_Q = 1.00, \quad x_Q' = 1.00$$

$$x_{AD} = 2.09, \quad x_{AD}' = 0.25, \quad x_{AQ} = 0.85, \quad x_{AQ}' = 0.85$$

$$\sigma_f = 0.00272 \quad \sigma_a = 0.0117$$

A comparison of calculated and test results is shown in Figs. 11 to 25, inclusive, for the 20-hp. machine, and in Figs. 5 to 8 for the 7000-kv-a. machine. Each illustration shows,

a. Calculated curve, from equations in Appendix A.
b. Oscillograph record of test.
c. Equation, with numerical values substituted,* from which the calculated curve was derived.

The reason for making extensive tests on the induction machine, excited by direct current as a synchronous machine, has been stated in the second footnote under "Results."

A careful inspection of each of the figures will clearly show a satisfactory agreement between the calculated and test curves, even with respect to the minute details. It will be noted that the decrements agree well.

The ordinates of the curves, it will be remembered, are scaled as the ratio of the actual value of the quantity to the value taken as the *per-unit* base. Ordinarily, normal value is chosen as that base. In the present case, however, the base for the 20-hp. machine was taken as 10 kv-a., 57.7 volts line-to-neutral, thus making the per-unit value of reactance numerically the same as the value in ohms—merely as a matter of convenience. The normal values were taken as the basis for the 7000-kv-a. machine. These points should be kept in mind in reading the ordinates.

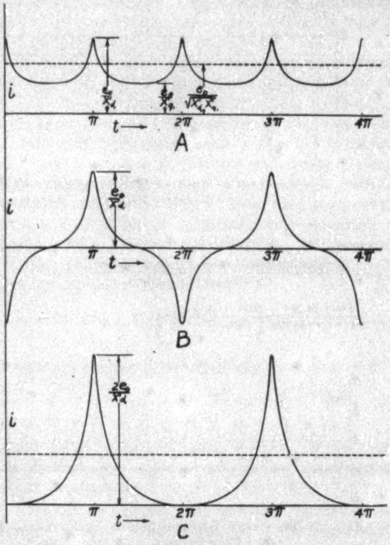

FIG. 9

In the case of the open-phase voltage during short circuit, Figs. 7 and 19, the ordinate gives the ratio of the voltage before short circuit to the voltage after short circuit.

With reference to the 7000-kv-a. alternator, this machine has no closed circuits on the rotor except the main field winding and the massive steel of the rotor spider. The effect of the latter is probably negligible. The poles themselves are, of course, laminated. The tests were taken at a relatively low voltage—at 300 volts; hence the premises were pretty closely approximated, and consequently the calculated results agree closely with the tests.

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*These equations, being reduced for numerical calculation, are in a somewhat different form from those in the summary of equations in Appendix A.

In the case of the voltage across the field terminals, *i. e.*, across the external impedance, the value of this impedance was not definitely known. Hence with the estimated value, the general shape of the calculated curve is all that may be expected to agree with the test. The calculated curve for this is shown in Fig. 8, the test curve in Fig. 6c.

### ACKNOWLEDGMENTS

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## Appendix A

### SUMMARY OF EQUATIONS

In the first part of the paper, under "Scope," it was stated that the present treatment develops expression for,

1. Armature Current—Appendix B.
2. Field Current—Appendix C.

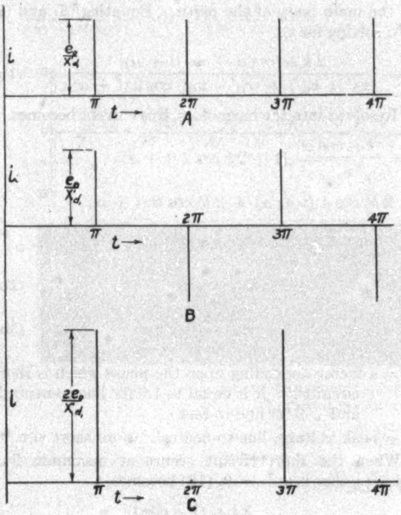

FIG. 10

3. Voltage Across Reactance in Armature Circuit—Appendix D.
4. Voltage Across Reactance in Field Circuit—Appendix E.
5. Voltage Across Open Phase—Appendix F.

These expressions are derived in the appendixes mentioned before, but for ease of reference, they are tabulated here. The order is as stated: First, the general equation for the quantity is given. Equations for special conditions follow readily from this. Thus, for the condition of maximum flux linkages at the instant of short circuit, $\alpha = 0$; while for minimum flux linkages $\alpha = \pi/2$ and the armature decrement is absent. Steady state conditions are obtained by placing $\alpha = \pi/2$, and omitting the armature and field decrements.

Since the equations are somewhat long it is found advisable to put them in a simpler form. By inspection, it is observed that they contain small groups which are more or less common to all of the expressions. These few groups, therefore, may be represented by a single symbol, as follows:

$A = x_D' + x_Q'$

$B = x_D' - x_Q'$

$C = x_D + x_Q'$

$F = x_D - x_Q'$

$G = x_D - x_D'$

$H = (x_D' + x_Q') + (x_D' - x_Q') \cos 2\,(t + \alpha)$
$\quad = A + B \cos 2\,(t + \alpha)$

$J = (x_D' + x_Q') - (x_D' - x_Q') \cos 2\,t$
$\quad = A - B \cos 2\,t$

$$K = \frac{x_D' + \sqrt{x_D'\,x_Q'}}{x_D + \sqrt{x_D'\,x_Q'}}$$

$$N = \sqrt{\frac{x_D'}{x_Q'}}$$

$$P = \frac{x_D - x_D'}{x_D + \sqrt{x_D'\,x_Q'}}$$

$$\sigma_a = \frac{r}{\sqrt{x_D'\,x_Q'}}$$

$$\sigma_f = \frac{\sigma_0}{K} \text{ (general)}$$

$$\sigma_f = \sigma_0 \sqrt{\frac{x_Q'}{x_D'}} \text{ (for cylindrical, laminated rotor only)}$$

$$\sigma_0 = \frac{R}{X}$$ (If $R$ and $X$ are in ohms, $\sigma_0$ will be a numeric, in proper terms to use in the above expressions).

### 1. ARMATURE CURRENT

*Transient.*

$$i = \frac{2\,k\,e_0}{H}\left[\epsilon^{-\sigma_a t} \cos \alpha - K \cos (t+\alpha) - P\,\epsilon^{-\sigma_f t} \cos (t+\alpha)\right]$$

For maximum flux linkages $\alpha = 0$ in the above equation, but for minimum flux linkages $\alpha = \pi/2$ and the armature decrement does not appear. Thus, for the latter case,

$$i = \frac{2\,k\,e_0}{J}\sin t\,[K + P\,\epsilon^{-\sigma_f t}]$$

*Sustained.* $$i = \frac{2\,k\,e_0\,K\sin t}{J}$$

### 2. Field Current

*Transient.*

$$I = \frac{e_0}{H}\,\{\,[C + F\cos 2\,(t+\alpha)\,]\,[K + P\,\epsilon^{-\sigma_f t}]$$
$$-\,2\,G\cos(t+\alpha)\cos\alpha\,\epsilon^{-\sigma_a t}\,\}$$

For maximum flux linkages $\alpha = 0$; and for minimum linkages,

$$I = \frac{e_0}{J}\,\{\,[C - F\cos 2\,t]\,[K + P\,\epsilon^{-\sigma_f t}]\,\}$$

*Sustained.* $$I = \frac{e_0\,K}{J}\,(C - F\cos 2\,t)$$

### 3. Voltage Across Reactor in Armature Circuit

$$e_{x_e} = \frac{2\,k\,e_0\,x_e}{H^2}\,[2\,B\cos\alpha\sin 2\,(t+\alpha)\,\epsilon^{-\sigma_a t}$$
$$+\sin(t+\alpha)\,[H - 4\,B\cos^2(t+\alpha)]\,(K + P\,\epsilon^{-\sigma_f t})\,]$$

For maximum linkages $\alpha = 0$; and for minimum linkages,

$$e_{x_e} = \frac{2\,k\,e_0\,x_e}{J}\,[\cos t\,(J - 4\,B\sin^2 t)\,(K + P\,\epsilon^{-\sigma_f t})\,]$$

*Sustained.* $$e_{x_e} = \frac{2\,k\,e_0\,x_e\,K}{J}\cos t\,(J - 4\,B\sin^2 t)$$

### 4. Voltage Across Reactance in Field Circuit

$$Ex_e = \frac{2\,G\,E_0\,X_e\cos\alpha\sin(t+\alpha)}{H^2}[H - 4\,B\cos^2(t+\alpha)]\,\epsilon^{-\sigma_a t}$$
$$+\,\frac{2\,P\,E_0\,X_e\sin 2\,(t+\alpha)}{H^2}\,(B\,C - A\,F)\,\epsilon^{-\sigma_f t}$$
$$+\,\frac{2\,K\,E_0\,X_e\sin 2\,(t+\alpha)}{H^2}\,(B\,C - A\,F)$$

For maximum flux linkages $\omega = 0$; while for minimum linkages $\alpha = \pi/2$ and

$$Ex_e = \frac{2\,P\,E_0\,X_e}{J^2}\sin 2\,t\,(A\,F - B\,C)\,\epsilon^{-\sigma_f t}$$
$$+\,\frac{2\,K\,E_0\,X_e}{J^2}\sin 2\,t\,(A\,F - B\,C)$$

*Sustained.* $$Ex_e = \frac{2\,K\,E_0\,X_e}{J^2}\sin 2\,t\,(A\,F - B\,C)$$

### 5. Voltage Across the Open Phase

*Transient.* $$e_1 = \frac{2\,k\,k_1\,B\,e_0}{H^2}\cos\alpha\,[\,H\cos 2\,(t+\alpha)$$
$$+\,B\sin^2 2\,(t+\alpha)\,]\,\epsilon^{-\sigma_a t}$$
$$+\,\frac{k_1\,e_0}{k\,H^2}\,\{\,[H^2\,k - 2\,k\,B\,H\cos 2\,(t+\alpha)$$
$$-\,2\,k\,B^2\sin^2 2\,(t+\alpha)]\cos(t+\alpha)$$
$$+\,k\,B\,H\sin(t+\alpha)\sin 2\,(t+\alpha)\,\}\,[K - (1-K)\,\epsilon^{-\sigma_f t}\,]$$

For maximum flux linkages $\alpha = 0$, while for minimum flux linkages $\alpha = \pi/2$ and

$$e_1 = \frac{k_1\,e_0}{k\,H^2}\,\{[H^2\,k + 2\,k\,B\,H\cos 2\,t + 2\,k\,B^2\sin^2 2\,t)]\sin t$$
$$+\,k\,B\,H\cos t\sin 2\,t\,\}\,[(1-K)\,\epsilon^{-\sigma_f t}\,K]$$

*Steady State.* $$e_1 = -\,\frac{k_1\,e_0\,K}{k\,H^2}\,\{\,k\,B\,H\cos t\sin 2\,t$$
$$+\,[H^2\,k + 2\,k\,B\,H\cos 2\,t + 2\,k\,B^2\sin^2 2\,t)]\sin t\}$$

## Appendix B

### Armature Current

Refer to "Premises" and "Fundamental Equations" in the main body of the paper. Equating (**5**) and (**6**) and solving for $i$,

$$i = \frac{2\,k\,e_0\,[\cos\alpha - \cos(t+\alpha)]}{(x_D' + x_Q') + (x_D' - x_Q')\cos 2\,(t+\alpha)} \qquad \textbf{(1b)}$$

Resolved into the harmonics, this current becomes,

$$i = \frac{k\,e_0\cos\alpha}{\sqrt{x_D'\,x_Q'}}\,[1 + 2\,b\cos 2\,(t+\alpha)$$
$$+\,2\,b^2\cos 4\,(t+\alpha) + 2\,b^3\cos 6\,(t+\alpha) + \ldots\,]$$
$$-\,\frac{2\,k\,e_0}{x_D' + \sqrt{x_D'\,x_Q'}}\,[\cos(t+\alpha) + b\cos 3\,(t+\alpha)$$
$$+\,b^2\cos 5\,(t+\alpha) + \ldots\,] \qquad \textbf{(2b)}$$

where $$b = \frac{\sqrt{x_Q'} - \sqrt{x_D'}}{\sqrt{x_Q'} + \sqrt{x_D'}} \qquad \textbf{(3b)}$$

$k$ = a factor depending upon the phase which is short circuited. It is equal to 1.0 for line-to-neutral, and $\sqrt{3}$ for line-to-line.

$e_0$ = peak voltage, line-to-neutral, before short circuit.

When the short circuit occurs at maximum flux linkages, that is at $\alpha = 0$, (**1b**) becomes,

$$\underset{\alpha = 0}{i} = \frac{2\,k\,e_0\,(1 - \cos t)}{(x_D' + x_Q') + (x_D' - x_Q')\cos 2\,t} \qquad \textbf{(4b)}$$

and (**2b**) becomes,

$$\underset{\alpha = 0}{i} = \frac{k\,e_0}{\sqrt{x_D'\,x_Q'}}\,[1 + 2\,b\cos 2\,t + 2\,b^2\cos 4\,t$$
$$+\,2\,b^3\cos 6\,t + \ldots\,]$$

$$- \frac{2\,k\,e_0}{x_D' + \sqrt{x_D'\,x_Q'}} [\cos t + b \cos 3\,t + b^2 \cos 5\,t + \;.\;.] \qquad \textbf{(5b)}$$

When the short circuit occurs at zero flux linkages, that is at $\alpha = \dfrac{\pi}{2}$, (**1b**) becomes,

$$\underset{\alpha\,=\,\pi/2}{i} = \frac{2\,k\,e_0 \sin t}{(x_D' + x_Q') - (x_D' - x_Q') \cos 2\,t} \qquad \textbf{(6b)}$$

and (**2b**) becomes,

$$\underset{\alpha\,=\,\pi/2}{i} = \frac{2\,k\,e_0}{x_D' + \sqrt{x_D'\,x_Q'}} [\sin t - b \sin 3\,t$$

$$+ b^2 \sin 5\,t - b^3 \sin 7\,t + \;.\;\;.\;\;.\;] \qquad \textbf{(7b)}$$

It is interesting to note that from equation (**2b**), the reactance which, with the voltage $k\,e_0$, determines the fundamental component of short-circuit current is

$$\frac{x_D' + \sqrt{x_D'\,x_Q'}}{2}$$

and that which, with the same voltage, determines the direct-current component is $\sqrt{x_D'\,x_Q'}$ The peak value of the fundamental is

$$i_1 = - \frac{2\,k\,e_0}{x_D' + \sqrt{x_D'\,x_Q'}}. \qquad \textbf{(8b)}$$

and the direct-current component is,

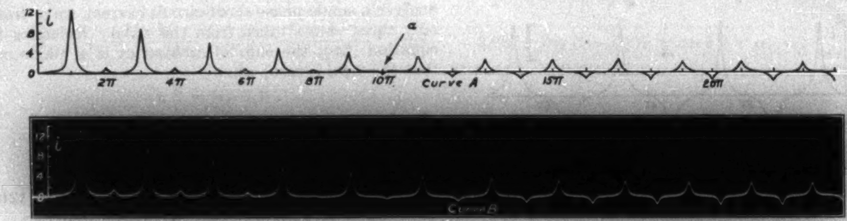

FIG. 11—TRANSIENT ARMATURE CURRENT, MAXIMUM INITIAL ARMATURE LINKAGES ON SINGLE-PHASE LINE-TO-LINE SHORT-CIRCUIT, 20-HP. MACHINE

A—Calculated curve
B—Test curve

Equation:—

$$i = \frac{3.46}{3.98 - 3.56 \cos 2\,t}\,\epsilon^{-0.0474t} - \frac{0.818 \cos t}{3.98 - 3.56 \cos 2\,t} - \frac{2.64 \cos t}{3.98 - 3.56 \cos 2\,t}\,\epsilon^{-0.132t}$$

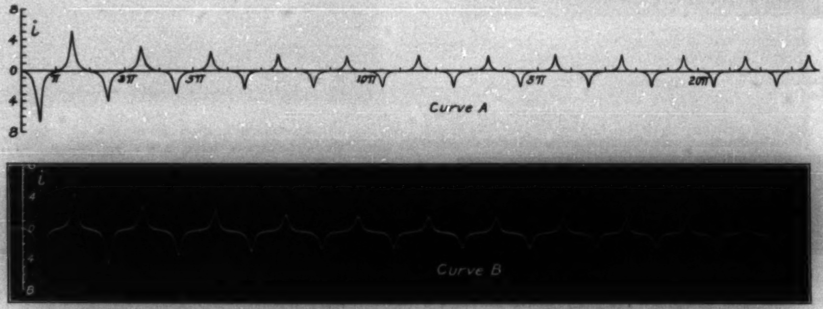

FIG. 12—TRANSIENT ARMATURE CURRENT, ZERO ARMATURE LINKAGES ON SINGLE-PHASE LINE-TO-LINE SHORT-CIRCUIT 20-HP. MACHINE

A—Calculated curve
B—Test curve

Equation:—

$$i = \frac{0.818 \sin t}{3.98 + 3.56 \cos 2\,t} - \frac{2.64 \sin t}{3.98 + 3.56 \cos 2\,t}\,\epsilon^{-0.132t}$$

$$i_0 = \frac{k\, e_0 \cos \alpha}{\sqrt{x_D{}'\, x_Q{}'}} \qquad (9\mathbf{b})$$

The effective value of the series in equation (**2b**) will now be derived. This value is the square root of the sum of the squares of the individual effective values. The coefficient of each harmonic term represents the peak value. Thus, dividing each harmonic term by $\sqrt{2}$ and squaring, and taking the square root of the sum, the effective value of the even harmonic series is

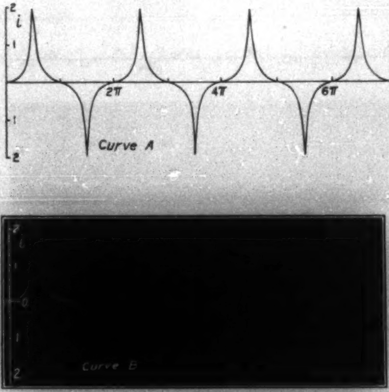

FIG. 13—SUSTAINED ARMATURE CURRENT ON SINGLE-PHASE LINE-TO-LINE SHORT-CIRCUIT 20-HP. MACHINE

A—Calculated curve
B—Test curve

Equation:— $i = \dfrac{0.818 \sin t}{3.98 + 3.56 \cos 2\,t}$

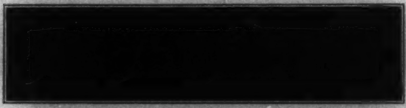

FIG. 14—SUSTAINED ARMATURE CURRENT, SINGLE-PHASE LINE-TO-LINE SHORT CIRCUIT WITH $x_D{}' = x_Q{}'$ 20-HP. MACHINE

$$i_{eff} = \frac{k\, e_0 \cos \alpha}{\sqrt{x_D{}'\, x_Q{}'}} \sqrt{1 + 2\,b^2 + 2\,b^4 + 2\,b^6 + \ldots}$$

or

$$i_{eff} = \frac{k\, e_0 \cos \alpha}{\sqrt{x_D{}'\, x_Q{}'}} \sqrt{\frac{1 + b^2}{1 - b^2}} \qquad (10\mathbf{b})$$

And for the odd harmonic series,

$$i_{eff}{}' = \frac{\sqrt{2}\, k\, e_0}{x_D{}' + \sqrt{x_D{}'\, x_Q{}'}} \sqrt{1 + b^2 + b^4 + b^6 + \ldots}$$

or

$$i_{eff}{}' = \frac{\sqrt{2}\, k\, e_0}{x_D{}' + \sqrt{x_D{}'\, x_Q{}'}} \; \frac{1}{\sqrt{1 - b^2}} \qquad (11\mathbf{b})$$

Equations (**10b**) and (**11b**) give the effective value of the respective series as a fraction of the peak value of normal fundamental current. To place the results in terms of the effective value of normal current, multiply each equation by $\sqrt{2}$.

Turn now to the relations which make it possible to analyze a single-phase short-circuit current wave from only three values taken from the wave. Referring to equation (**2b**), the sum of *each* series is a maximum (but the total is zero) when

$$(t + \alpha) = 2\,\pi$$

$$i = \frac{k\, e_0 \cos \alpha}{\sqrt{x_D{}'\, x_Q{}'}} \left[1 + 2\,b + 2\,b^2 + 2\,b^3 + 2\,b^4 + \ldots\right]$$

$$- \frac{2\,k\, e_0}{x_D{}' + \sqrt{x_{-}{}'\, x_Q{}'}} \left[1 + b + b^2 + b^3 + \ldots\right] \qquad (12\mathbf{b})$$

Taking the summation of these series,

$$i = \frac{k\, e_0 \cos \alpha}{\sqrt{x_D{}'\, x_Q{}'}} \; \frac{1 + b}{1 - b} - \frac{2\,k\, e_0}{x_D{}' + \sqrt{x_D{}'\, x_Q{}'}} \; \frac{1}{1 - b} \qquad (13\mathbf{b})$$

Substituting (**8b**) and (**9b**) in (**13b**), the peak value of the odd harmonic series is thus $1/(1 - b)$ times the peak value of the fundamental component $i_1$, and the peak value of the even harmonic series is $(1 + b)/(1 - b)$ times the direct-current component $i_0$. Thus, for the sum of the odd harmonics, the peak value is

FIG. 15—SUSTAINED ARMATURE CURRENT SINGLE-PHASE LINE-TO-LINE SHORT CIRCUIT WITH $x_D{}' > x_Q{}'$ 20-HP. MACHINE

$$i_{odd} = i_1/(1 - b) \qquad (14\mathbf{b})$$

Similarly, the peak value of the even harmonic series is

$$i_{ev} = i_0\left[(1 + b)/(1 - b)\right] \qquad (15\mathbf{b})$$

Substituting for $b$ its value from (**3b**), some additional interesting relations are incidentally obtained. Thus

$$\frac{1}{1 - b} = \frac{\sqrt{x_Q{}'} + \sqrt{x_D{}'}}{2\,\sqrt{x_D{}'}} \qquad (16\mathbf{b})$$

and

$$\frac{1 + b}{1 - b} = \sqrt{\frac{x_Q{}'}{x_D{}'}} \qquad (17\mathbf{b})$$

Substituting (**8b**) and (**16b**) in (**14b**),

$$i_{odd} = \frac{k\, e_0}{x_D{}'} \qquad (18\mathbf{b})$$

and (**9b**) and (**17b**) in (**15b**),

$$i_{ss} = \frac{k\, e_0 \cos \alpha}{x_D'} \qquad \textbf{(19b)}$$

The relations are shown graphically in Fig. 9.

Consider now the value of the sum of the two series in (**2b**) at three different values of $t + \alpha$, namely, $\frac{\pi}{4}$, $\frac{\pi}{2}$, and $\pi$. First, when $t + \alpha = \frac{\pi}{4}$, or 45 deg.

$$i_{45} = i_0 \frac{1 - b^2}{1 + b^2} - \sqrt{2}\, i_1 \frac{1 - b}{1 + b^2} \qquad \textbf{(20b)}$$

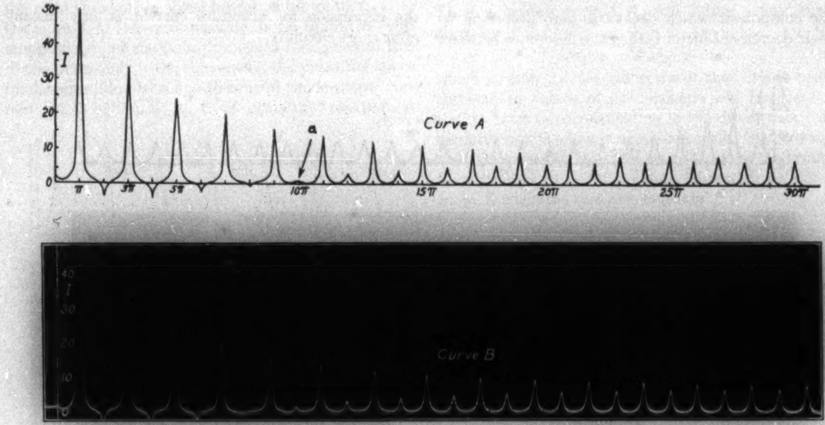

FIG. 16—TRANSIENT FIELD CURRENT, MAXIMUM INITIAL ARAMATURE LINKAGES ON SINGLE-PHASE LINE-TO-LINE SHORT-CIRCUIT 20-HP. MACHINE

**A—Calculated curve**
**B—Test Curve**

**Equation:** –

$$I = \frac{12.3 \cos t}{3.98 - 3.56 \cos t}\, \epsilon^{-0.474t} + \frac{3.08}{3\text{-}98 - 3.56 \cos 2t} + \frac{9.97}{3.98 - 3.56 \cos 2t}\, \epsilon^{-0132t}$$

when $t + \alpha = \frac{\pi}{2}$, or 90 deg.,

$$i_{90} = i_0 \frac{1 - b}{1 + b} \qquad \textbf{(21b)}$$

and when $t + \alpha = \pi$, or 180 deg.,

$$i_{180} = i_0 \frac{1 + b}{1 - b} + i_1 \frac{1}{1 - b}. \qquad \textbf{(22b)}$$

From these three equations, the entire wave can be analyzed. For illustration, let $i_{45} = -0.332$, $i_{90} = 0.5$, and $i_{180} = 6.0$. The three equations thus determine $b$, $i_0$, and $i_1$. They are

$$b = 0.333 \quad i_0 = 1.0 \quad i_1 = 2.667$$

Hence, by (**2b**) the wave is

$$i = 1 + \frac{2}{3} \cos 2\,(t + \alpha) + \frac{2}{9} \cos 4\,(t + \alpha) + \frac{2}{27} \cos 6\,(t + \alpha) + \ldots$$

$$- 2.667 \left[ \cos\,(t + \alpha) + \frac{1}{3} \cos 3\,(t + \alpha) + \frac{1}{9} \cos 5\,(t + \alpha) + \ldots \right]$$

When the wave has no d-c. component $i_0$, the analysis is much simpler, since only two values from the wave are now needed; namely, the value at 45 deg. and at 90 deg.

*Transient Armature Currents.* The armature current immediately after short circuit is given by equation (**1b**). The term which disappears when $\alpha = \pi/2$ contains the direct current component and the even harmonics. As time elapses, these currents decay to zero according to the armature decrement factor, $\sigma_a$, derived in Appendix H. The other term contains the odd harmonics which are proportional to the field current at every instant. Hence this component of equation (**1b**) decays from the value shown to a sustained value

$$\frac{x_D' + \sqrt{x_D' \, x_Q'}}{x_D + \sqrt{x_D' \, x_Q'}}$$

times as great, according to the field decrement factor, $\sigma_f$, derived in Appendix H.

The sustained armature current is thus

$$\underset{\text{sustained}}{i} = -\,2\,k\,e_0 \left[ \frac{x_D' + \sqrt{x_D' \, x_Q'}}{x_D + \sqrt{x_D' \, x_Q'}} \right]$$

$$\frac{\cos\,(t + \alpha)}{(x_D' + x_Q') + (x_D' - x_Q')\cos 2\,(t + \alpha)} \qquad (\mathbf{23b})$$

The component which decays to zero according to the field decrement factor is then the difference between the second term of equation (**1b**) and equation (**23b**). The total armature current at any instant after short circuit is then

$$i = \frac{2\,k\,e_0 \cos\alpha}{(x_D' + x_Q') + (x_D' - x_Q')\cos 2\,(t + \alpha)}\,\epsilon^{-\sigma_a t}$$

$$-\,\frac{2\,k\,e_0\,(x_D - x_D')\cos\,(t + \alpha)}{(x_D + \sqrt{x_D' \, x_Q'})\,[\,(x_D' + x_Q') + (x_D' - x_Q')\cos 2\,(t + \alpha)\,]}\,\epsilon^{-\sigma_f t}$$

$$-\,2\,k\,e_0 \left[ \frac{x_D' + \sqrt{x_D' \, x_Q'}}{x_D + \sqrt{x_D' \, x_Q'}} \right]$$

$$\frac{\cos\,(t + \alpha)}{(x_D' + x_Q') + (x_D' - x_Q')\cos 2\,(t + \alpha)} \qquad (\mathbf{24b})$$

If we substitute from equation (**1b**) and (**2b**) the relations

$$\frac{\cos\alpha}{(x_D' + x_Q') + (x_D' - x_Q')\cos 2\,(t + \alpha)}$$

$$= \frac{\cos\alpha}{\sqrt{x_D' \, x_Q'}}\ \text{[even series]} \qquad (\mathbf{25b})$$

and,

$$\frac{\cos\,(t + \alpha)}{(x_D' + x_Q') + (x_D' - x_Q')\cos\,(t + \alpha)}$$

$$= \frac{1}{x_D' + \sqrt{x_D' \, x_Q'}}\ \text{[odd series]} \qquad (\mathbf{26b})$$

the expression for armature current at any instant after short circuit is

$$i = \frac{2\,k\,e_0 \cos\alpha}{\sqrt{x_D' \, x_Q'}}\ \text{[even series]}\ \epsilon^{-\sigma_a t}$$

$$\frac{-\,2\,k\,e_0\,(x_D - x_D')}{(x_D + \sqrt{x_D' \, x_Q'})\,(x_D' + \sqrt{x_D' \, x_Q'})}\ \text{[odd series]}\ \epsilon^{-\sigma_f t}$$

$$\frac{-\,2\,k\,e_0}{x_D + \sqrt{x_D' \, x_Q'}}\ \text{[odd series]} \qquad (\mathbf{27b})$$

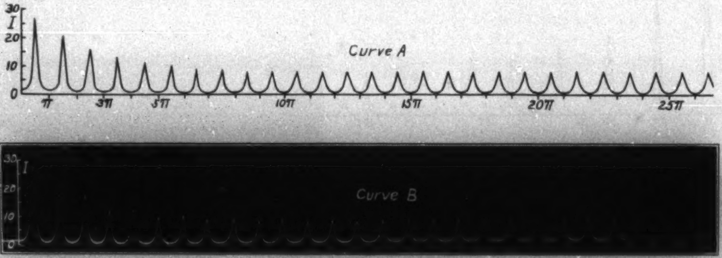

FIG. 17—TRANSIENT FIELD CURRENT, ZERO INITIAL ARMATURE LINKAGES ON SINGLE-PHASE LINE-TO-LINE SHORT-CIRCUIT 20-HP. MACHINE

A—Calculated curve
B—Test curve (not quite zero flux linkages)

Equation:—

$$I = \frac{3.08}{3\,98 + 3.56\cos 2\,t} + \frac{9.97}{3.98 + 3.56\cos 2\,t}\,\epsilon^{-0.132t}$$

## Appendix C

### FIELD CURRENT

The equation for the *initial* field current will be obtained in accordance with the plan outlined under "Fundamental Equations."

It is convenient to take the three-phase normal values of current and armature reaction as the bases of the *per-unit* quantities, both three-phase and single-phase. Thus a three-phase *per-unit* current *i* will produce a rotating space fundamental m. m. f. whose amplitude, expressed as a fraction of the amplitude corresponding to normal current, is numerically equal to the current $i$. The single-phase m. m. f. and current will be expressed in terms of these.

It will be recalled that the amplitude of the synchronously rotating component of space fundamental m. m. f. due to normal frequency current in one phase of a three-phase machine, is one-half of the amplitude of the *total* pulsating space fundamental produced by that current, the other half rotating oppositely; and that the corresponding synchronously rotating components of the other two phases happen to be in space phase with that of the first. That is, the amplitude of the total three-phase space fundamental m. m. f., *i. e.*, the m. m. f. of armature reaction, is 1.5 times the total amplitude $A_1$ of the pulsating space fundamental due to one phase only. Or, conversely, the pulsating space fundamental due to a line-to-neutral single-phase current is 2/3 of the m. m. f. of armature reaction $A$ due to a three-phase current of the same value. Since the space fundamental $A_1$ at any instant is independent of the nature of the variation of the current $i$ which exists at that instant, it follows that, in general, any single-phase current $i$ will produce a space fundamental

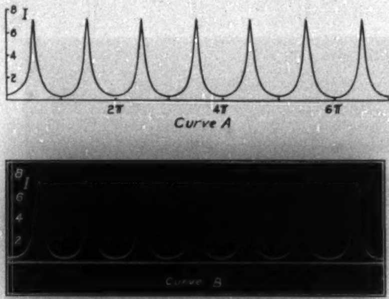

FIG. 18—SUSTAINED FIELD CURRENT ON SINGLE-PHASE LINE-TO-LINE SHORT CIRCUIT 20-HP. MACHINE

A—Calculated curve
B—Test curve

Equation:—

$$i = \frac{3.08}{3.98 + 3.56 \cos 2t}$$

$$A_1 = 2/3\, k\, A = 2/3\, k\, i \qquad \textbf{(1c)}$$

where $k$ = unity for line-to-neutral current, and 1.73 for a line-to-line current. And obviously $A_1$ will vary in time according as $i$ varies.

When the rotor is moving, the space fundamental m. m. f. $A_1$ will have relative motion with respect to the rotor poles, but at any instant it may be resolved into the two conventional components; $A_D$ in the direct axis, and $A_Q$ in the quadrature axis. If the single-phase armature current is due to a short circuit at the instant the direct axis is displaced from the axis of the single-phase winding by an angle $\alpha$, the component of $A_1$ which remains in the direct axis is

$$A_D = 2/3\, k\, i \cos (t + \alpha) \qquad \textbf{(2c)}$$

and in the quadrature axis

$$A_Q = 2/3\, k\, i \sin (t + \alpha) \qquad \textbf{(3c)}$$

It has been shown in *Synchronous Machines—III* that unit m. m. f., in suddenly appearing over the direct axis, will induce a *per-unit* field current

$$\Delta I_d = x_d - x_d' \qquad \textbf{(4c)}$$

or, since *per-unit* field current is numerically equal to *per-unit* nominal voltage,

$$\Delta I_d = \Delta e_d$$

Thus, a sudden m. m. f. $A_d$ will induce a field current given by

$$\Delta e_d = - A_d (x_d - x_d') \qquad \textbf{(5c)}$$

where $x_d$ and $x_d'$ are respectively the line-to-neutral, three-phase values of synchronous and transient *per-unit* reactances corresponding to the direct axis. (The negative sign is taken in accordance with the convention that the space fundamental m. m. f. due to the armature is considered to be in the same direction as the field m. m. f. when the two axes coincide).

Similarly, for the quadrature axis,

$$\Delta e_q = - A_q (x_q - x_q') \qquad \textbf{(6c)}$$

Since the quantities $A_d$ and $A_q$ in equations (**5c**) and (**6c**) each represent the amplitudes of a space fundamental m. m. f., expressed as a fraction of the amplitude of the space fundamental m. m. f., due to normal three-phase current, it follows that the amplitude of any space fundamental m. m. f., so expressed, such as $A_D$ or $A_Q$, may be directly substituted. Hence, from (**2c**) and (**3c**),

$$\Delta e_d = - \frac{2}{3} k\, i\, (x_d - x_d') \cos (t + \alpha) \qquad \textbf{(7c)}$$

and $$\Delta e_q = - \frac{2}{3} k\, i\, (x_q - x_q') \cos (t + \alpha) \qquad \textbf{(8c)}$$

If the main field winding is the only rotor winding in the direct axis, the field current $\Delta I_d$, or $\Delta e_d$, will exist entirely in the winding. However, if there are other short-circuited rotor windings in the direct axis, only a part of $\Delta e_d$ will appear in the main field windings, the remainder appearing in the other closed rotor circuits. For the case of a single rotor winding, the field current $\Delta I_d$ which is produced by the armature m. m. f. due to the armature current $i$, is obtained by substituting in (**7c**) the value of $i$ given by equation (**1b**) in Appendix B. Thus,

$$\Delta I_d = \frac{- \dfrac{4}{3} k^2 e_0 (x_d - x_d') \cos (t + \alpha) [\cos \alpha - \cos (t + \alpha)]}{(x_D' + x_Q') + (x_D' - x_Q') \cos 2 (t + \alpha)} \qquad \textbf{(9c)}$$

It is desirable to express $(x_d - x_d')$ in terms of $x_D - x_D')$.

Referring to the definitions and equations in Appendix I,

$$x_d - x_d' = \frac{3}{2k^2}(x_D - x_D') \qquad \textbf{(10c)}$$

Substituting this in (**9c**),

$$\Delta I_d = \Delta e_d$$

$$= \frac{-2\, e_0\, (x_D - x_D') \cos(t + \alpha)\, [\cos \alpha - \cos(t + \alpha)\,]}{(x_D' + x_Q') + (x_D' - x_Q') \cos 2\,(t + \alpha)} \qquad \textbf{(11c)}$$

The total *per-unit* field current, or *per-unit* nominal voltage immediately after short circuit, that is the *initial* value, is

$$I_d = (I_0 + \Delta I_d) = e_d = (e_0 + \Delta e_d) \qquad \textbf{(12c)}$$

$$I_d = e_d = \frac{e_0\,(x_D + x_Q') + (x_D - x_Q')\cos 2\,(t + \alpha) - 2\,(x_D - x_D')\cos \alpha \cos(t + \alpha)}{(x_D' + x_Q') + (x_D' - x_Q')\cos 2\,(t + \alpha)} \qquad \textbf{(13c)}$$

When the harmonic series form for $i$ from equation (**2b**), Appendix B, is substituted in (**7c**) and remembering the relation in (**10c**),

$$I_d = e_d = \frac{e_0\,(x_D + \sqrt{x_D'\, x_Q'})}{x_D' + \sqrt{x_D'\, x_Q'}}$$

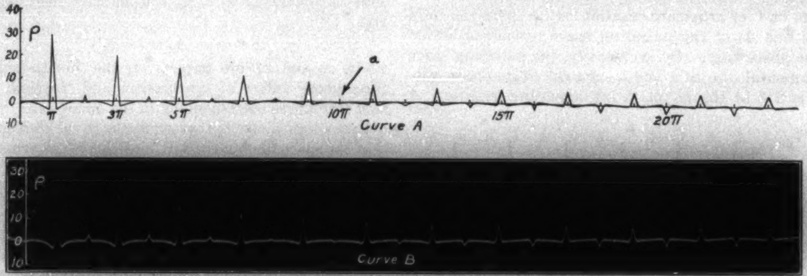

FIG. 19—TRANSIENT OPEN-PHASE VOLTAGE, MAXIMUM INITIAL ARMATURE LINKAGE ON SINGLE-PHASE LINE-TO-LINE SHORT-CIRCUIT 20-HP. MACHINE

A—Calculated curve
B—Test curve
Equation:—

$$e = -7.12\,\frac{(3.56 - 3.98\cos 2t)}{(3.98 - 3.56\cos 2t)}\,\epsilon^{-0.0471t} - \frac{1.78\cos t - 3.36\cos t\sin^2 t}{3.98 - 3.56\cos 2t} + \frac{5.98\cos t\sin^2 2t}{(3.98 - 3.56\cos 2t)^2}$$

$$- \frac{(5.75\cos t - 10.9\cos t\sin^2 t)}{(3.98 - 3.56\cos 2t)^2}\,\epsilon^{-0.132t} + \frac{(19.3\cos t\sin^2 2t)}{(3.98 - 3.56\cos 2t)^2}\,\epsilon^{-0.132t}$$

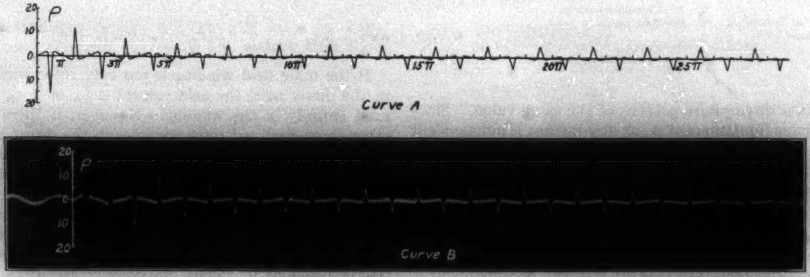

FIG. 20—TRANSIENT OPEN-PHASE VOLTAGE, ZERO INITIAL ARMATURE LINKAGES ON SINGLE-PHASE LINE-TO-LINE SHORT-CIRCUIT 20-HP. MACHINE

A—Calculated curve
B—Test curve

Equation:—

$$e' = \frac{-1.78\sin t - 3.36\sin t\cos^2 t}{3.98 + 3.56\cos 2t} + \frac{5.98\sin t\sin^2 2t}{(3.98 + 3.56\cos 2t)^2} - \frac{5.75\sin t - 10.9\sin t\cos^2 t}{3.98 + 3.56\cos 2t}\,\epsilon^{-0.132t} + \frac{19.3\sin t\sin^2 2t}{3.98 + 3.56\cos 2t^2}\,\epsilon^{-0.132t}$$

$$- \frac{e_0 (x_D - x_D')(1 + b) \cos \alpha}{\sqrt{x_D' x_Q'}} [\cos (t + \alpha)$$
$$+ b \cos 3 (t + \alpha) + b^2 \cos 5 (t + \alpha) + \ldots]$$
$$+ \frac{e_0 (x_D - x_D')}{x_D' + \sqrt{x_D' x_Q'}} (1 + b) [\cos 2 (t + \alpha)$$
$$+ b \cos 4 (t + \alpha) + b^2 \cos 6 (t + \alpha) + \ldots] \quad \textbf{(14c)}$$

The quadrature component $\Delta I_q$ may be obtained in a similar manner.

The field current comprises a direct current component, a series of odd harmonics, whose amplitudes are in geometric ratio, and a series of even harmonics whose amplitudes are in geometric ratio. The geometric ratio is the same in all cases, for the armature current as well as for the field current, and its value is given by equation (**3b**), Appendix B.

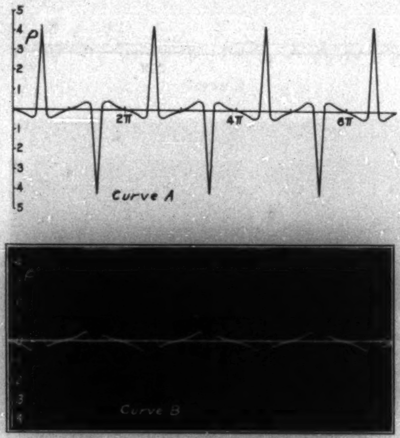

FIG. 21—SUSTAINED OPEN-PHASE VOLTAGE ON SINGLE-PHASE LINE-TO-LINE SHORT-CIRCUIT 20-HP. MACHINE

A—Calculated curve
B—Test curve

Equation:—

$$e = \frac{1.78 \sin t - 3.36 \sin t \cos^2 t}{3.98 + 3.56 \cos 2 t} + \frac{5.98 \sin t \sin^2 2 t}{[3.98 + 3.56 \cos 2 t]^2}$$

*Transient Field Current.* It will be noticed that the average field current or nominal voltage increases at short circuit in the ratio

$$\frac{x_D + \sqrt{x_D' x_Q'}}{x_D' + \sqrt{x_D' x_Q'}}$$

As time elapses, this average field current will decay to the value existing before short circuit according to the field decrement factor $\sigma_f$ derived in Appendix H. Since all even harmonics in the field current are proportional to the average field current at every instant after short circuit, they will also decay to their sustained values in the same manner. The odd harmonics in the field current are proportional to the direct-current component in the armature at every instant and thus decay to zero according to the armature decrement factor $\sigma_a$ derived in Appendix H. In equation (**13c**), the odd harmonics comprise those terms which disappear when $\alpha = \frac{\pi}{2}$, *i. e.*, when there is no direct current component in the armature. The remaining terms comprise the average value and all even harmonics. Thus

$$\underset{\text{odd}}{I_d} = \frac{- 2 e_0 (x_D - x_D') \cos \alpha \cos (t + \alpha)}{(x_D' + x_Q') + (x_D' - x_Q') \cos 2 (t + \alpha)} \quad \textbf{(15c)}$$

and

$$\underset{\text{even}}{I_d} = \frac{e_0 [(x_D + x_Q') + (x_D - x_Q') \cos 2 (t + \alpha)]}{(x_d' + x_Q') + (x_D' - x_Q') \cos 2 (t + \alpha)} \quad \textbf{(16c)}$$

The sustained value of (**15c**) is zero and the sustained value of (**16c**) bears the same relation to (**16c**) as the final average value bears to the initial average value. Hence the sustained field current is

$$\underset{\text{sustained}}{I_d} = \frac{x_D' + \sqrt{x_D' x_Q'}}{x_D + \sqrt{x_D' x_Q'}}$$
$$e_0 \left[ \frac{(x_D + x_Q') + (x_D - x_Q') \cos 2 (t + \alpha)}{(x_D' + x_Q') + (x_D' - x_Q') \cos 2 (t + \alpha)} \right] \quad \textbf{(17c)}$$

The differences between (**16c**) and (**17c**) thus decays to zero according to the field decrement factor, and the expression for the total field current at any instant after short circuit is

$$I = \frac{- 2 e_0 (x_D - x_D') \cos \alpha \cos (t + \alpha)}{(x_D' + x_Q') + (x_D' - x_Q') \cos 2 (t + \alpha)} \epsilon^{-\sigma_a t}$$
$$+ \frac{x_D - x_D'}{x_D + \sqrt{x_D' x_Q'}}$$
$$e_0 \left[ \frac{(x_D + x_Q') + (x_D - x_Q') \cos 2 (t + \alpha)}{(x_D' + x_Q') + (x_D' - x_Q') \cos 2 (t + \alpha)} \right] \epsilon^{-\sigma_f t})$$
$$+ \frac{x_D' + \sqrt{x_D' x_Q'}}{x_D + \sqrt{x_D' x_Q'}}$$
$$e_0 \left[ \frac{(x_D + x_Q') + (x_D - x_Q') \cos 2 (t + \alpha)}{(x_D' + x_Q') + (x_D' - x_Q') \cos 2 (t + \alpha)} \right] \quad \textbf{(18c)}$$

If we substitute the odd harmonic series from equation (**14c**) for (**15c**), and the average value and even harmonics from equation (**14c**) for equation (**16c**), equation (**18c**) may be written

$$I = \frac{-e_0\,(x_D - x_D')\,(1+b)\cos\alpha}{\sqrt{x_D'\,x_Q'}}\,[\text{odd series}]\,\epsilon^{-\sigma_a t}$$
$$+ \frac{e_0\,(x_D - x_D')^2\,(1+b)}{(x_D' + \sqrt{x_D'\,x_Q'})\,(x_D + \sqrt{x_D'\,x_Q'})}[\text{even series}]\,\epsilon^{-\sigma_f t}$$
$$+ \frac{e_0\,(x_D - x_D')}{x_D' + \sqrt{x_D'\,x_Q'}}\,\epsilon^{-\sigma_f t} \qquad \textbf{(19c)}$$
$$+ \frac{e_0\,(x_D - x_D')\,(1+b)}{x_D + \sqrt{x_D'\,x_Q'}}\,[\text{even series}]$$
$$+ e_0$$

## Appendix D

### VOLTAGE ACROSS EXTERNAL REACTANCE IN ARMATURE CIRCUIT

The reactances, $x_D'$ and $x_Q'$, may in general include an external reactance $x_e$. It is then of interest to find the voltage which exists across this reactance under conditions of sudden short circuit. The per-unit value of voltage will be given by the product of the external inductance and the rate of change of current with respect to time. Since per-unit reactance at normal frequency is numerically equal to per-unit inductance, the voltage is,

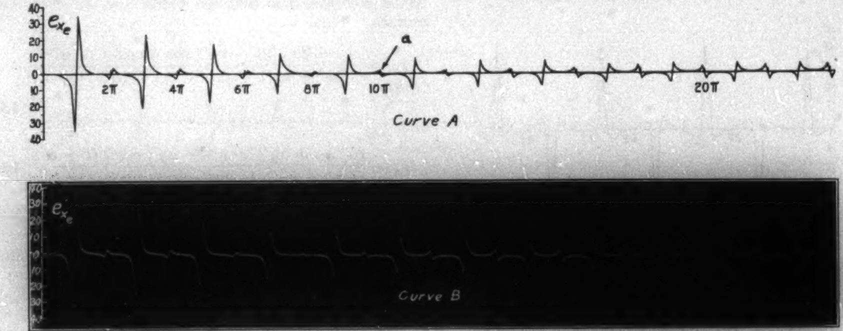

FIG. 22—TRANSIENT VOLTAGE ACROSS AN EXTERNAL REACTOR IN THE ARMATURE CIRCUIT, MAXIMUM INITIAL ARMATURE LINKAGES ON SINGLE-PHASE LINE-TO-LINE SHORT-CIRCUIT 20-HP. MACHINE

A—Calculated curve
B—Test curve

Equation:—

$$e = -\frac{0\ 164}{3.98 - 3.56\cos 2t}\,\epsilon^{-0.0474t} - \frac{24.6\sin 2t}{(3.98 - 3.56\cos 2t)^2}\,\epsilon^{-0.0474t}$$
$$+ 0.815\,\frac{7.12\cos t\sin 2t + (3.98 - 3.56\cos 2t)\sin t}{(3.98 - 3.56\cos 2t)^2}$$
$$+ 2.64\,\frac{7.12\cos t\sin 2t + (3.98\cos 2t)\,(\sin t + 0.132\cos t)}{(3.98 - 3.56\cos 2t)^2}\,\epsilon^{-0.132t}$$

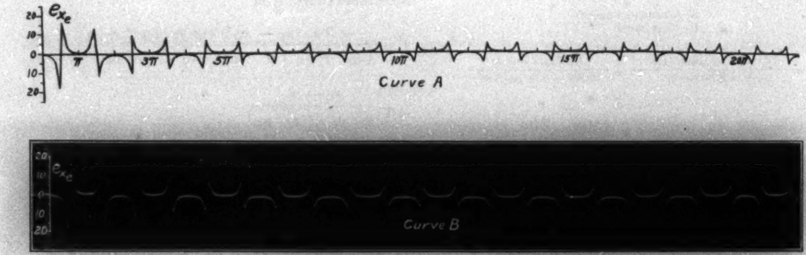

FIG. 23—TRANSIENT VOLTAGE ACROSS AN EXTERNAL REACTOR IN THE ARMATURE CIRCUIT, ZERO INITIAL ARMATURE LINKAGES ON SINGLE-PHASE LINE-TO-LINE SHORT-CIRCUIT 20-HP. MACHINE

A—Calculated curve
B—Test curve

Equation:—

$$e = -0.815\,\left(\frac{7.12\sin 2t\sin t + (3.98 + 3.56\cos 2t)\cos t}{(3.98 + 3.56\cos 2t)^2}\right.$$
$$-\ 2.64\,\frac{7.12\sin 2t\sin t + (3.98 + 3.56\cos 2t)\,(\cos t - .132\sin t)}{(3.98 + 3.56\cos 2t)^2}\,\epsilon^{-0.132t}$$

$$e_{x_e} = x_e \frac{d\,i}{d\,t} \qquad \textbf{(1d)}$$

The initial value of short-circuit armature current is given by equation (**1b**) of Appendix B. Hence, from this expression, the voltage across the external reactance, assuming no decrements in the current wave, will be

$$e_{x_e} = \frac{2\,k\,e_0\,x_e}{H^2}\,[\,H \sin(t+\alpha)$$

$$+\,2\,B \sin 2\,(t+\alpha)\,[\cos\alpha - \cos(t+\alpha)]\,] \qquad \textbf{(2d)}$$

The symbolic form is that outlined in Appendix A.

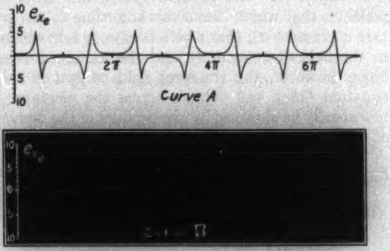

FIG. 24—SUSTAINED VOLTAGE ACROSS AN EXTERNAL REACTOR IN THE ARMATURE CIRCUIT ON SINGLE-PHASE LINE-TO LINE SHORT-CIRCUIT 20-HP. MACHINE

A—Calculated curve
B—Test curve

Equation:—

$$e = 0.815 \left[\frac{-\,7.12 \sin 2\,t \sin t \,-\, (3.98 + 3.56 \cos 2\,t) \cos t}{(3.98 + 3.56 \cos 2\,t)^2}\right]$$

Under the development of Transient Armature Current of Appendix B, it was shown that part of the current wave decays to zero according to the armature decrement $\sigma_a$, and that a second part decays to zero according to the field decrement $\sigma_f$. The third part is the steady-state value. Thus, the above voltage equation will have components which also decay to zero according to these two decrements.

That part of equation (**2d**) which contains the armature decrement corresponds to the first term of equation (**24b**) and is

$$\frac{4\,k\,e_0\,x_e\,B \sin 2\,(t+\alpha)\cos\alpha}{H^2}\,\epsilon^{-\sigma_a t} \qquad \textbf{(3d)}$$

With reference to (**24b**), it will be noticed that a second term, containing the derivatives of the exponential, should be introduced in order to be exact. However, since this quantity is very small in comparison with (**3d**) and will never be noticeable in practical cases, it is not considered here. That is, the voltage due to the rate of change of current which in turn is due to the armature decrement is neglected.

The remainder of (**2d**) is that portion which contains the field decrement $\sigma_f$, and which decays from the value shown to a sustained value

$$\frac{x_D' + \sqrt{x_D'\,x_Q'}}{x_D + \sqrt{x_D'\,x_Q'}} = K$$

times as great, according to this decrement. It is divided into the alternating component which finally dies away, and the sustained value, in the same manner as its corresponding currents of equation (**1b**) were formed into the second and third terms of equation (**24b**).

As an alternative to decomposing (**2d**) into the above mentioned components, the transient voltage across an external reactance in the armature circuit may be more easily obtained by differentiating (**24b**). Neglecting those terms concerned with derivatives of the exponents we have,

$$e_{x_e} = \frac{2\,k\,e_0\,x_e}{H^2}\,[\,2\,B \cos\alpha \sin 2\,(t+\alpha)\,\epsilon^{-\sigma_a t}$$

$$+\,[H \sin(t+\alpha) - 2\,B \cos(t+\alpha) \sin 2\,(t+\alpha)]\,(K + P\,\epsilon^{-\sigma_f t}] \qquad \textbf{(4d)}$$

It is interesting to treat the initial voltage in series form and observe the shapes of the total and component waves. Thus, using the series expression for current as given by equation (**2b**), the voltage across the external reactance becomes,

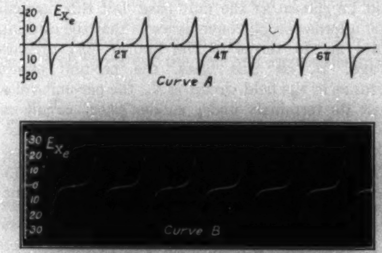

FIG. 25—SUSTAINED VOLTAGE ACROSS AN EXTERNAL REACTOR IN THE FIELD CIRCUIT ON SINGLE-PHASE LINE-TO LINE SHORT-CIRCUIT 20 HP. MACHINE

A—Calculated curve
B—Test curve (inverted)

$$= \frac{21.9 \sin 2\,t}{(3.98 + 3.56 \cos 2\,t)^2}$$

$$e_{x_e} = -\,\frac{k\,e_0\,x_e \cos\alpha}{\sqrt{x_D'\,x_Q'}}\,[\,4\,b \sin 2\,(t+\alpha)$$

$$+\,8\,b^2 \sin 4\,(t+\alpha) + 12\,b^3 \sin 6\,(t+\alpha) + \;.\;.\;.\,]$$

$$+\,\frac{2\,k\,e_0\,x_e}{x_D' + \sqrt{x_D'\,x_Q'}}\,[\sin(t+\alpha) + 3\,b \sin 3\,(t+\alpha)$$

$$+\,5\,b^2 \sin 5\,(t+\alpha) + \;.\;.\;.\,] \qquad \textbf{(5d)}$$

When $\alpha = 0$, the first series will have the general form shown by Fig. 25 in the main body of the paper, while the second series will have the form shown by Fig. 24. The total wave is given by Fig. 22.

## Appendix E

### VOLTAGE ACROSS EXTERNAL REACTANCE IN FIELD CIRCUIT

Under conditions of sudden short circuit, alternating currents are produced in the field circuit. When this circuit contains some reactance external to the field winding proper, such as the exciter armature, alternating voltages exist across the reactance. It may sometimes be desirable to determine such voltages.

As before, for a pure reactance, the per-unit voltage is given by the product of the per-unit external inductance (which is numerically equal to the per-unit reactance $X_e$), and the rate of change of current; in this case, field current.

In evaluating this voltage, it is convenient to express the external reactance in field terms. Unit field voltage is defined as the d-c. voltage corresponding, by Ohm's Law, to unit field current. The unit value of either resistance or reactance is thus the ratio of unit field voltage to unit field current. Any other value of ohms could be chosen as the unit base, but this particular value affords special convenience in that the calculated results are in terms of the known field excitation voltage. If, on this basis, the per-unit external reactance in the field circuit is $X_e$, the per-unit voltage across its terminals under sudden short circuit conditions is the product of $X_e$ and the rate of change of field current.

The initial field current is given by equation (**13c**), hence the voltage across the reactance at the instant of short circuit is

$$E_{X_e} = \frac{2\,E_0\,X_e}{H^2}\,\{\,H\,G\cos\alpha\sin(t+\alpha) + \sin 2\,(t+\alpha)\,[\,B\,C - H\,F + F\cos 2\,(t+\alpha) - 2\,G\cos\alpha\cos(t+\alpha)\,]\,\} \tag{1e}$$

Expressed in series form (**1e**) becomes

$$E_{X_e} = \frac{E_0\,X_e\,G\,(1+b)\cos\alpha}{\sqrt{x_D'\,x_Q'}}\,[\sin(t+\alpha) + 3\,b\sin 3\,(t+\alpha) + 5\,b^2\sin 5\,(t+\alpha) + \ldots] - \frac{2\,E_0\,X_e\,G\,(1+b)}{x_D' + \sqrt{x_D'\,x_Q'}}\,[\sin 2\,(t+\alpha) + 2\,b\sin 4\,(t+\alpha) + 3\,b^2\sin 6\,(t+\alpha) + \ldots] \tag{2e}$$

Referring to Appendix B, it will be remembered that, under sustained short circuit, only the odd harmonics are present in the armature current. Hence, only the d-c. component and the even harmonics will exist in the field current for sustained short circuit, as explained in Appendix C. These field currents, given by their respective components of equations (**13c**) and (**14c**) are

$$\underset{\text{sustained}}{I_d} = E_0\,K\left[\frac{C + F\cos 2\,(t+\alpha)}{A + B\cos 2\,(t+\alpha)}\right] \tag{3e}$$

$$\text{or}\quad \underset{\text{sustained}}{I_d} = E_0 + E_0\,P\,(1+b)\,[\cos 2\,(t+\alpha) + b\cos 4\,(t+\alpha) + \ldots] \tag{4e}$$

The sustained voltage across the field reactance is thus

$$E_{X_e} = \frac{2\,E_0\,X_e\,K\sin 2\,(t+\alpha)}{H^2}\,(B\,C - A\,F) \tag{5e}$$

$$\text{or}\quad E_{X_e} = -\,2\,E_0\,P\,(1+b)\,[\sin 2\,(t+\alpha) + 2\,b\sin 4\,(t+\alpha) + 3\,b^2\sin 6\,(t+\alpha) + \ldots] \tag{6e}$$

Equation (**1e**) can be decomposed into three components; that which dies away according to the armature decrement $\sigma_a$, that which decays to zero according to the field decrement $\sigma_f$, and the sustained voltage. Since, however, the transient field current is known, equation (**18c**), the voltage across the reactance can more easily be obtained by the product of the derivative of this expression and $X_e$. Thus,

$$E_{X_e} = \frac{2\,E_0\,X_e\,G}{H^2}\cos\alpha\sin(t+\alpha)\,[\,H - 4\,B\cos^2(t+\alpha)\,]\,\epsilon^{-\sigma_a t} + \frac{2\,E_0\,X_e\,P}{H^2}\sin 2\,(t+\alpha)\,[B\,C - A\,F\,]\,\epsilon^{-\sigma_f t} + \frac{2\,E_0\,X_e\,K}{H^2}\sin 2\,(t+\alpha)\,[\,B\,C - A\,F\,] \tag{7e}$$

As in the case of the voltage across an external reactance in the armature circuit, the terms containing the derivatives of the decrements have been omitted because they are quite inappreciable. It will be observed that the last term of (**7e**), representing the sustained voltage across a field reactance, is exactly equation (**5e**).

## Appendix F

### VOLTAGE ACROSS THE OPEN PHASE

It has been shown that the current in the short-circuited phase produces a space fundamental m. m. f.

$$A = 2/3\,k\,i \tag{1f}$$

of which the component in the direct axis is

$$A_D = 2/3\,k\,i\cos(t+\alpha) \tag{2f}$$

and the component in the quadrature axis is

$$A_Q = 2/3\,k\,i\sin(t+\alpha) \tag{3f}$$

Under sudden short-circuit conditions, the space fundamental fluxes produced are

$$\varphi_D = 2/3\,k\,i\,x_{ad}'\cos(t+\alpha) \tag{4f}$$

$$\varphi_Q = 2/3\,k\,i\,x_{aq}'\sin(t+\alpha) \tag{5f}$$

The components of these fluxes which an open winding whose axis is at an angle $\beta$ from the axis of the short-circuited winding are respectively,

$$\varphi_1 = 2/3\,k\,i\,x_{ad}'\cos(t+\alpha)\cos(t+\alpha+\beta) \tag{6f}$$

and $\varphi_2 = 2/3\, k\, i\, x_{aq}' \sin(t + \alpha) \sin(t + \alpha + \beta)$ **(7f)**

The flux linkages due to these fluxes are

$$\psi_1 = 2/3\, k\, k_1\, i\, x_{ad}' \cos(t + \alpha) \cos(t + \alpha + \beta) \quad \textbf{(8f)}$$

and $\psi_2 = 2/3\, k\, k_1\, i\, x a_q{}' \sin(t + \alpha) \sin(t + \alpha + \beta)$ **(9f)**

where $k_1$ is a constant by which per-unit fundamental flux must be multiplied to give the flux linkages in the open winding under consideration. For a line to neutral winding, $k_1$ is unity and for a line to line winding $k_1$ is $\sqrt{3}$.

The current in the short-circuited winding also produces mutual flux linkages with the open-circuited winding such as those due to space harmonics, mutual slot fluxes, mutual fluxes in the end turn leakage paths, etc. The flux linkages from this source are

$$\psi_3 = i\, x_m \quad \textbf{(10f)}$$

The flux linkages in the open-circuited winding due to the rotor current existing before short circuit are

$$\psi_3 = k_1\, e_0 \cos(t + \alpha + \beta) \quad \textbf{(11f)}$$

The total flux linkages in the open winding at any instant after short circuit are then

$$\psi = \psi_1 + \psi_2 + \psi_3 + \psi_4 \quad \textbf{(12f)}$$

Using the relations, similar to equation (**13i**), that

$$x_{ad}' + x_{aq}' = \frac{3}{2\,k^2}(x_{AD}' + x_{AQ}') \quad \textbf{(13f)}$$

$$x_{ad}' - x_{aq}' = \frac{3}{2\,k^2}(x_{AD}' - x_{AQ}') \quad \textbf{(14f)}$$

the total flux linkages are

$$\psi = k_1\, e_0 \cos(t + \alpha + \beta) + i\, x_m + \frac{k_1\, i}{2\,k}$$
$$[(x_{AD}' + x_{AQ}') \cos\beta + (x_{AD}' - x_{AQ}') \cos(2\,t + 2\,\alpha + \beta)] \quad \textbf{(15f)}$$

The voltage induced in the open winding when another winding in the machine is short-circuited is given by the negative rate of change of equation (**15f**), or

$$e_1 = k_1\, e_0 \sin(t + \alpha + \beta)$$
$$+ \frac{k_1}{k}(x_{AD}' - x_{AQ}') \sin(2\,t + 2\,\alpha + \beta)\, i$$
$$- \left\{ x_m + \frac{k_1}{2\,k} [\,(x_{AD}' + x_{AQ}') \cos\beta \right.$$
$$\left. + (x_{AD}' - x_{AQ}') \cos(2\,t + 2\,\alpha + \beta)\,] \right\} \frac{d\,i}{d\,t} \quad \textbf{(16f)}$$

Substituting the value of current from equation (**1b**), and its derivative, and using the notation of Appendix A, this voltage becomes

$$e_1 = k_1\, e_0 \sin(t + \alpha + \beta) + \frac{2\,k\,e_0}{H}$$
$$(x_{AD}' - x_{AQ}') \sin(2\,t + 2\,\alpha + \beta) [\cos\alpha - \cos(t + \alpha)\,]$$
$$- \frac{2\;k\;e_0}{H} \sin(t + \alpha) \left\{ x_m + \frac{k_1}{2\,k} \right.$$
$$\left. [(x_{AD}' + x_{AQ}') \cos\beta + (x_{AD}' - x_{AQ}') \cos(2\,t + 2\,\alpha + \beta)] \right\}$$
$$- \frac{4\,k\,e_0\,B}{H^2} \sin 2\,(t + \alpha)$$
$$[\cos\alpha - \cos(t + \alpha)\,] \left\{ x_m + \frac{k_1}{2\,k} [(x_{AD}' + x_{AQ}') \right.$$
$$\left. \cos\beta + (x_{AD}' - x_{AQ}') \cos(2\,t + 2\,\alpha + \beta)\,] \right\} \quad \textbf{(17f)}$$

When normal current flows through one winding of the armature, flux linkages will be produced in the other windings. Of these linkages, the larger part is due to space fundamental fluxes. The remainder are due to non-space fundamental fluxes such as mutual slot fluxes, mutual fluxes in the end turn leakage paths, etc. These linkages are represented by $x_m$. In many cases, this is small compared with the space fundamental flux linkages and by assuming it to be zero many of the equations are greatly simplified.

For ordinary values of $\beta$ which exist in synchronous machines (60 deg. and 90 deg.) equation (**17f**) essentially has its maximum when $t = 180 - \alpha$. For this value of $t$, all terms but the first and second disappear and

$$e_{1m} = -\,k_1\, e_0 \sin\beta \left[ \frac{x_Q'}{x_D'}(1 + \cos\alpha) - \cos\alpha \right] \quad \textbf{(18f)}$$

When $\beta$ is very small this value is in error since for $\beta = 0$ deg. there will be a voltage in the open phase corresponding to leakage reactance voltage in the short-circuited phase. For values of $\beta$ approaching zero it is necessary to plot the voltage curve to find its maximum value.

The open phase voltage can also be expressed in the harmonic form by substituting the current expression from equation (**2b**), and its derivative. In this harmonic form, if we make the approximation that

$$x_{AD}' - x_{AQ}' = (x_D' - x_Q') \quad \textbf{(19f)}$$

and let $\beta = \frac{\pi}{2}$, then $x_m = 0$, and the *fundamental voltage* in the open phase is found to be

$$e_1 = k_1\, e_0\, (1 + b) \cos(t + \alpha) \quad \textbf{(20f)}$$

The fundamental voltage in an open-circuited phase 90 deg. away from the short-circuited phase will thus be increased by the ratio $(1 + b)$, as mentioned in the main body of the paper.

When the short circuit occurs when maximum flux links the winding, *i. e.*, when $\alpha = 0$, the voltage on the open phases will have the general form shown in Fig. 19

When $\alpha = \frac{\pi}{2}$, no flux links the winding at the instant of short circuit and the voltage on the open phase may be of the form shown in Fig. 20.

If the short circuit occurs line to neutral, the winding comprised of the two unshort-circuited phases in series is in space quadrature with the short-circuited phase. Then

$$\beta = \pi/2$$
$$k_1 = \sqrt{3}$$
$$x_m = 0$$
$$k = 1$$

For $\alpha = 0$, equation (**17f**) then becomes, (using the simplified notation),

$$e_1 = k\,e_0 \cos t + \frac{2\,k\,e_0}{H}\,(x_{AD}' - x_{AQ}')\cos 2\,t\,(1 - \cos t)$$
$$+ \frac{k\,e_0}{H}\,(x_{AD}' - x_{AQ}')\sin t \sin 2\,t$$
$$+ \frac{2\,k\,B\,e_0}{H^2}\,(x_{AD}' - x_{AQ}')\sin^2 2\,t\,(1 - \cos t) \quad \textbf{(21f)}$$

When $\alpha = \frac{\pi}{2}$, equation (**17f**) becomes

$$e_1 = -\,k\,e_0 \sin t - \frac{2\,k\,e_0}{J}\,(x_{AD}' - x_{AQ}')\sin t \cos 2\,t$$
$$- \frac{k\,e_0}{J}\,(x_{AD}' - x_{AQ}')\cos t \sin 2\,t$$
$$+ \frac{2\,k\,B\,e_0}{J^2}\,(x_{AD}' - x_{AQ}')\sin t \sin^2 2\,t \quad \textbf{(22f)}$$

As pointed out before, practically all the difference between $x_D'$ and $x_Q'$ is due to the difference in space fundamental flux, a negligible amount being due to the variation in leakage fluxes in the two axes. Hence, for all practical purposes, $(x_D' - x_Q')$ may be taken equal to $(x_{AD}' - x_{AQ}')$, which simplifies equations (**21f**) and (**22f**), some of the terms combining into more compact terms. Equation (**21f**) has a maximum when $t = \pi$. For this value of $t$

$$e_1 = -\,k\,e_0 \left[\frac{2\,x_Q'}{x_D'} - 1\right] \quad \textbf{(23f)}$$
$$\alpha = 0$$
$$\beta = \frac{\pi}{2}$$
$$t = \pi$$

The voltage on this winding before short circuit is $k\,e_0$. Hence, the voltage at short-circuit line-to-neutral may rise to $\frac{2\,x_Q'}{x_D'} - 1$ times the voltage before short circuit on the open phases.

Equation (**22f**) has a maximum when $t = \pi/2$.

Then

$$e_1 = -\,k\,e_0 \left[\frac{x_Q'}{x_D'}\right]$$
$$\alpha = \frac{\pi}{2}$$
$$\beta = \frac{\pi}{2}$$
$$t = \frac{\pi}{2} \quad \textbf{(24f)}$$

Equation (**17f**) may be decomposed into a form which clearly shows the components affected by the armature and field decrements, and the steady-state term. Thus, substituting for $(x_{AD}' - x_{AQ}')$ and omitting $x_m$, equation (**17f**) becomes

$$e_1 = \frac{2\,k\,k_1\,B \cos\alpha\,e_0}{H^2}\,[\,H \cos 2\,(t + \alpha)$$
$$+ B \sin^2 2\,(t + \alpha)\,]\,\epsilon^{-\sigma_a t}$$
$$+ \frac{k_1\,e_0}{k\,H^2}\,\{\,[H^2\,k - 2\,k\,B\,H \cos 2\,(t + \alpha)$$
$$- 2\,k\,B^2 \sin^2 2\,(t + \alpha)\,]\cos(t + \alpha)$$
$$+ k\,B\,H \sin(t + \alpha)\sin 2\,(t + \alpha)\}\,[K - (1 - K)\,\epsilon^{-\sigma_f t}\,] \quad \textbf{(25f)}$$

This is the open phase voltage for any condition of transiency, *i. e.*, for any flux originally trapped in the armature at the time of short circuit. For maximum flux linkages $\alpha = 0$ and all terms appear. For minimum flux linkages $\alpha = \frac{\pi}{2}$ and that term containing the armature decrement does not appear. The steady-state voltage is obtained by neglecting all terms containing either the armature or field decrements.

## Appendix G

### VARIATION OF ARMATURE INDUCTANCE WITH POSITION

The object of resolving a sine wave of m. m. f. into two components is to obtain fluxes which are in space phase with the m. m. fs. In dealing with synchronous machines, resolution is made about the direct and quadrature axes, and the reactance of a single-phase armature winding in any position with respect to these axes, due to the space fundamental flux produced by the space fundamental m. m. f., may be obtained as follows.

Assume a single-phase armature winding with the axis of the winding at an angle $\gamma$ from the direct axis of the machine. When a current $i$ of normal frequency flows through this winding a space fundamental m. m. f. of amplitude

$$A = \frac{2}{3}\,k\,i \cos t \quad \textbf{(1g)}$$

is produced. The component of $A$ in the direct axis is

$$A_{\mathrm{D}} = \frac{2}{3}\, k\, i \cos \gamma \cos t \tag{2g}$$

and the component in the quadrature axis is

$$A_{\mathrm{Q}} = \frac{2}{3}\, k\, i \sin \gamma \cos t \tag{3g}$$

The m. m. f. in the direct axis produces a space fundamental flux in this axis proportional to the m. m. f. If there are no short-circuited secondary windings in this axis, the proportionality factor between m. m. f. and line-to-neutral linkages is $x_{ad}$,* or, in general $k\, x_{ad}$.

Then, $$\psi_{\mathrm{D}} = \frac{2}{3}\, k^2\, i\, x_{ad} \cos \gamma \cos t \tag{4g}$$

Likewise, in the quadrature axis

$$\psi_{\mathrm{Q}} = \frac{2}{3}\, k^2\, i\, x_{aq} \sin \gamma \cos t \tag{5g}$$

The component of $\psi_{\mathrm{D}}$ which is in space phase with the armature winding, thus linking the winding, is

$$\psi_1 = \psi_{\mathrm{D}} \cos \gamma = \frac{2}{3}\, k^2\, i\, x_{ad} \cos^2 \gamma \cos t$$

$$= \frac{2}{3}\, k^2\, i\, x_{ad} \left[ \frac{1}{2} + \frac{1}{2} \cos 2\gamma \right] \cos t \tag{6g}$$

Also, the component of $\psi_{\mathrm{Q}}$ in space phase with the armature winding is

$$\psi_2 = \frac{2}{3}\, k^2\, i\, x_{aq} \sin^2 \gamma \cos t$$

$$= \frac{2}{3}\, k^2\, i\, x_{aq} \left[ \frac{1}{2} - \frac{1}{2} \cos 2\gamma \right] \cos t \tag{7g}$$

The linkages due to the total flux in space phase with the winding is

$$\psi = \frac{2}{3}\, k^2\, i \left[ \frac{x_{ad} + x_{aq}}{2} + \frac{x_{ad} - x_{aq}}{2} \cos 2\gamma \right] \cos t \tag{8g}$$

The three-phase reactances, $x_{ad}$ and $x_{aq}$ may be expressed in terms of the corresponding reactances for the single-phase winding in question. When a current $i$ flows in a single-phase winding, the alternating stationary m. m. f., fundamental in space is $\frac{2}{3}\, k$ times the rotating m. m. f. produced when a three-phase current $i$ flows through a three-phase winding. If these m. m. fs. act on the same reluctance paths, the space fundamental fluxes will have the same relation as the m. m. fs. The flux linkages, produced by the single-phase current $i$ will then be $\frac{2}{3}\, k^2$ times the linkages produced by the same three-phase current $i$, and

$$x_{\mathrm{AD}} = \frac{2}{3}\, k^2\, x_{ad} \tag{9g}$$

and $$x_{\mathrm{AQ}} = \frac{2}{3}\, k^2\, x_{aq} \tag{10g}$$

Substituting these relations in (**8g**)

$$\psi = i \left[ \frac{x_{\mathrm{AD}} + x_{\mathrm{AQ}}}{2} + \frac{x_{\mathrm{AD}} - x_{\mathrm{AQ}}}{2} \cos 2\gamma \right] \cos t \tag{11g}$$

The induced voltage is $\dfrac{d\,\psi}{d\,t}$. Thus, remembering that $i$ is taken here as the amplitude of normal frequency current:

$$e = i \left[ \frac{x_{\mathrm{AD}} + x_{\mathrm{AQ}}}{2} + \frac{x_{\mathrm{AD}} - x_{\mathrm{AQ}}}{2} \cos 2\gamma \right] \sin t \tag{12g}$$

The coefficient of $i \sin t$ is the *per-unit* reactance of the single-phase winding due to the space fundamental flux produced by the space fundamental m. m. f., as a function of position when both the rotor and stator are stationary. Since *per-unit* reactance of a stationary circuit at normal frequency is numerically equal to the per-unit inductance of the circuit, this coefficient gives also the *per-unit* inductance; and when used as an inductance, is independent of the relative motion of the rotor and stator.

As pointed out in a previous paper,[9d] the leakage reactance also varies with position as a second harmonic of the angular displacement of the winding from the direct axis, *i. e.*,

$$x_{\mathrm{L}} = \frac{x_{\mathrm{LD}} + x_{\mathrm{LQ}}}{2} + \frac{x_{\mathrm{LD}} - x_{\mathrm{LQ}}}{2} \cos 2\gamma \tag{13g}$$

The total reactance may then be written

$$x = \frac{x_{\mathrm{D}} + x_{\mathrm{Q}}}{2} + \frac{x_{\mathrm{D}} - x_{\mathrm{Q}}}{2} \cos 2\gamma \tag{14g}$$

where, $$x_{\mathrm{D}} = x_{\mathrm{LD}} + x_{\mathrm{AD}} \tag{15g}$$

and, $$x_{\mathrm{Q}} = x_{\mathrm{LQ}} + x_{\mathrm{AQ}} \tag{16g}$$

## Appendix H

### DECREMENT FACTORS

*Field Decrement.* The theoretical basis for determining this is given in the main body of the paper under "Fundamental Equations." It is shown in Appendix C that the average field current—*i. e.*, the d-c. component, spontaneously increases at short circuit to a value

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*$x_{ad}$ is the three-phase reactance of armature reaction and applies here since the single-phase space fundamental m. m. fs. are expressed in terms of normal three-phase space fundamental m. m. f.

$$\frac{x_D + \sqrt{x_D' \, x_Q'}}{x_D' + \sqrt{x_D' \, x_Q'}}$$

times the value existing immediately before short circuit. Thus the increase in equivalent magnetic reluctance, as discussed in the above reference, is given by the same ratio, and the corresponding change in inductance is given by the reciprocal. Hence, assuming negligible armature resistance, as may be done without appreciable error in commercial machines, the field decrement factor is

$$\sigma_f = \frac{x_D + \sqrt{x_D' \, x_Q'}}{x_D' + \sqrt{x_D' \, x_Q'}} \, \sigma_0 \qquad \textbf{(1h)}$$

where $\sigma_0$ is the open circuit, field decrement factor,

$$\sigma_0 = \frac{\mathcal{R}}{\omega \, \mathcal{L}_0}$$

where $\mathcal{R}$ is the ohmic resistance of the field circuit, and $\mathcal{L}_0$ the *total* inductance, in henrys, of the field circuit, corresponding to the condition of open circuited armature, and $\omega$ is $2 \pi f$, where $f$ is normal frequency. These three quantities $\mathcal{R}$, $\mathcal{L}_0$, and $\omega$ are not *per-unit* quantities, but $\sigma_0$ is.

If appreciable resistance exists in the armature circuit the value of $\sigma_f$ given by (**1h**) will be decreased to the extent (discussed under "Fundamental Equations") which the equivalent inductance is thereby increased.

It is of interest to note that in the ideal case of a laminated cylindrical rotor where

$$x_Q' = x_Q = x_D$$

equation (**1h**) reduces to $\sigma_f = \sqrt{\dfrac{x_D}{x_D'}} \, \sigma_0$ (**2h**)

The decrement factors (**1h**) and (**2h**) give, of course, the average decrement, thus determining the direct component of transient current in the field, the envelope of the even harmonics in the field current, and the envelope of the odd harmonics of current in the armature. It can be shown that these decrement factors are rigorous for the envelopes and average component referred to, for the assumed case of zero armature resistance. Thus the only error involved is the slight difference in wave shape, the peaks being correct. The same thing is true of the armature decrement, derived below, under the assumption of zero field resistance.

*Armature Decrement.* The armature decrement applies to the treatment flux linkages which happen to be caught and "trapped" in the armature circuit when the latter is short-circuited. It is, of course, altogether a matter of chance of rotor position at the instant of short circuit, whether such linkages shall be zero, maximum value, or some intervening value; that is, there may be or may not be an "armature transient," and when it occurs, it may have any value between the above limits.

The value of trapped linkages is,

$$\psi = k \, e_0 \cos \alpha \qquad \textbf{(3h)}$$

The average current required to sustain these linkages is, by equation (**9b**) in Appendix B,

$$i_0 = \frac{k \, e_0 \cos \alpha}{\sqrt{x_D' \, x_Q'}}$$

Thus, the inductance to be used in the decrement factor is $\psi \div i_0$, or

$$L = \sqrt{x_D' \, x_Q'}$$

and the armature decrement factor is

$$\sigma_a = \frac{r}{\sqrt{x_D' \, x_Q'}} \qquad \textbf{(4h)}$$

where $r$ is the *per-unit* resistance of the short-circuited armature circuit, and $x_D'$ and $x_Q'$ represent the *per-unit static transient* inductance, (and also the corresponding *per-unit* reactance).

The decrement factor $\sigma_a$ applies to the d-c. component of the total armature current, the envelope of the even harmonic currents in the armature, and the envelope of the odd harmonics in the field current.

## Appendix I

### REACTANCES—DEFINITIONS AND RELATIONS

$x_d$ = synchronous reactance, three phase, line-to-neutral, direct axis, corresponding to open-circuited rotor windings.

$x_{ad}$ = reactance of armature reaction, thus due to the direct axis space fundamental air-gap flux, produced by three-phase currents. It is one component of $x_d$.

$x_{ld}$ = armature leakage reactance, three-phase, line-to-neutral, and is the other component of $x_d$. Thus,

$$x_d = x_{ad} + x_{ld} \qquad \textbf{(1i)}$$

$x_d'$ = transient reactance, three-phase, line-to-neutral, direct axis, corresponding to the total leakage flux between the armature and field windings. It thus corresponds to the total flux linkages of the armature winding occasioned by the sudden application of three-phase currents, when the field winding is closed, such flux linkages being only those which generate voltage of fundamental frequency. It comprises $x_{ld}$—that is, the leakage flux of the armature—plus additional space fundamental flux which crosses the air-gap, and corresponds in amount to the field leakage flux produced by the induced field current. The latter component is denoted by $x_{ad}'$. Thus

$$x_d' = x_{ld} + x_{ad}' \qquad \textbf{(2i)}$$

$x_D$ = *total* static reactance, single-phase, corresponding to the condition that, at stand-still, the direct axis coincides with the axis of the single-phase winding, and that the rotor windings are open-circuited. It thus corresponds to the total linkages produced by the armature current under those conditions. It will, of course, have a different value if the single-phase winding is considered to be line-to-line, from that if the winding is taken as line-to-neutral, the per-unit value being about three times as much in the former as in the latter case. It is analogous to the three-phase total reactance $x_d$.

$x_{AD}$ = static reactance, single-phase, corresponding to the space fundamental flux, direct axis under the above conditions. It is a component of $x_D$, and is analogous to the three-phase reactance of armature reaction $x_{ad}$.

$x_{LD}$ = static armature leakage reactance, single phase, direct axis, corresponding to the conditions specified under $x_D$. It is analogous to $x_{ld}$ and is the other component of $x_D$, that is, corresponds to all flux linkages not contained in the space fundamental. Thus,

$$x_D = x_{AD} + x_{LD} \tag{3i}$$

$x_D'$ = static transient reactance, single-phase, direct axis, corresponding to the conditions specified under $x_D$, except that the rotor windings are short-circuited. It corresponds to the total leakage flux between the armature and rotor windings, and is thus analogous to $x_d$. It thus comprises $x_{LD}$, and some additional space fundamental flux crossing the air-gap and corresponding in amount to the field leakage produced by the induced field current. The latter component is denoted by $x_{AD}'$. Thus,

$$x_D' = x_{LD} + x_{AD}' \tag{4i}$$

The corresponding symbols for all of the foregoing ten quantities for the quadrature axis are denoted by the subscript *q* instead of *d* for three-phase quantities, and by *Q* instead of *D* for the static single-phase quantities. Thus small letter subscripts indicate three-phase quantities, and capitals indicate static single-phase quantities.

There are certain additional important relations which exist between the above quantities. These relations will now be derived.

Subtracting equation (**4i**) from equation (**3i**),

$$x_D - x_D' = x_{AD} - x_{AD}' \tag{5i}$$

and, subtracting equation (**2i**) from (**1i**),

$$x_d - x_d' = x_{ad} - x_{ad}' \tag{6i}$$

Now the same space fundamental m. m. f., whether produced by a three-phase or a single-phase current, will produce in the same axis the same space fundamental linkages in a given winding. Thus, since by definition, the product of $x_{ad}$ by the amplitude of a space fundamental m. m. f. produced by a three-phase current direct axis will give line-to-neutral linkages of armature reaction, it follows that the product of $x_{ad}'$ by *any* space fundamental m. m. f. in the same axis will give line-to-neutral linkages. Hence, the line-to-neutral linkages, maximum value, due to a suddenly appearing space fundamental m. m. f. $A_D$, the latter being produced by a single-phase current, are,

$$\psi_D = A_D\, x_{ad}$$

when the rotor circuits are open-circuited, and are,

$$\psi_D' = A_D\, x_{ad}'$$

when the rotor circuits are closed. The line-to-line linkages would be *k* times these values, where $k = 1.0$ for line-to-neutral, 1.73 line-to-line. Thus in general

$$\psi_D = k\, A_D\, x_{ad} \tag{7i}$$

and

$$\psi_D' = k\, A_D\, x_{ad}' \tag{8i}$$

Subtracting (**8i**) from (**7i**),

$$\psi_D - \psi_D' = k\, A_D\, (x_{ad} - x_{ad}') \tag{9i}$$

But, by definition of *x*, $$\psi_D = i_D\, x_D \tag{10i}$$

and $$\psi_D' = i_D\, x_D' \tag{11i}$$

Subtracting these,

$$\psi_D - \psi_D' = i_D\, (x_D - x_D') \tag{12i}$$

Equating (**9i**) and (**12i**), and substituting the general relation from (**1c**) between the amplitude of the space fundamental m. m. f. produced by single-phase current, and the value of the current,

$$2/3\, k^2\, i_D\, (x_{ad} - x_{ad}') = i_D\, (x_D - x_D')$$

Therefore, substituting (**6i**),

$$x_d - x_d' = \frac{3}{2\,k^2}\, (x_D - x_D') \tag{13i}$$

## Nomenclature

*Per-unit* quantities, as outlined under "Discussion of Theory," are listed and defined below. The general scheme of notation involves the use of capital letters for field circuit quantities, small letters for the armature.

*For the Armature.* All voltages are expressed as a fraction of the peak value of normal armature voltage; currents, as a fraction of the peak value of normal armature current; flux, as a fraction of normal space fundamental flux, the latter corresponding to normal voltage at normal frequency on open circuit; linkages, as a fraction of the linkages corresponding to normal flux; inductance, as a fraction of unit inductance, the latter being defined by the ratio of normal linkages to normal current; and reactances (at fundamental frequency), as a fraction of unit reactance, the latter being defined by the ratio of normal voltage line-to-neutral to normal current.

*For the Field.* All voltages are expressed as a fraction of unit field voltage, *i. e.*, the direct voltage across the field corresponding to unit field current; currents, as a fraction of unit field current, *i. e.*, the direct current corresponding to normal a-c. terminal voltage on open circuit (no saturation); flux, as a fraction of normal flux, as defined above for the armature circuit; linkages, as a fraction of unit field linkages, the latter being defined as the linkages produced in the field winding by normal flux; inductance, as a fraction of that inductance which is defined as the ratio of unit field linkages to unit field current; reactance, as a fraction of unit field reactance, which is defined as the ratio of unit field voltage to unit field current.

With regard to the per-unit bases for field voltage and field reactance, it should be mentioned that there are other bases which, in certain cases, it might be more convenient to adopt. It is altogether a matter of convenience. For instance, if it should be of greater convenience to have symmetrical equations for the armature and field, than to have, as in the present case, the calculated results of field circuit voltage come out in terms of the known excitation voltage, then unit field voltage might be taken as the voltage which unit field linkages would generate in the field winding at normal frequency. Unit field reactance and resistance would then be changed accordingly.

$A$ = amplitude of space fundamental of armature m. m. f. Specific values of $A$ are:

- $A_d$ = m. m. f. in direct axis, produced by balanced polyphase current
- $A_q$ = corresponding value in quadrature axis
- $A_1$ = amplitude of m. m. f. produced by current at any instant in a single-phase winding.
- $A_D$ = component of $A_1$ in direct axis
- $A_Q$ = component of $A_1$ in quadrature axis

$b$ = geometric ratio defined by the relation following equation (**9**)

$e$ = instantaneous value of any armature voltage

$e_0$ = line-to-neutral voltage before short circuit

$e_d$ = nominal voltage due to direct axis excitation

$e_q$ = nominal voltage due to quadrature axis excitation

$\Delta e_d$ = increment in $e_d$ induced by transient field current

$\Delta e_q$ = increment in $e_q$ induced by transient field current

$E$ = field voltage in general

$E_0$ = field voltage preceding short circuit

$i$ = armature current in general

$I$ = field current in general

$I_d$ = field current in direct axis winding

$I_q$ = field current in quadrature axis winding

$\Delta I_d$ = increment in $I_d$ induced by transient armature current

$\Delta I_q$ = corresponding increment in $I_q$

$I_0$ = field current at the instant before short circuit

$k$ = voltage conversion factor for the short-circuited phase. $k = 1$ for line-to-neutral short circuit, and $= \sqrt{3}$ for line-to-line short circuit

$k_1$ = similar factor for the voltage generated in the open circuited phase

$l$ = inductance, in general, of the armature circuit

$l'$ = transient inductance of the armature, variable with respect to rotor position

$L$ = inductance, in general, of the field circuit

$\mathcal{L}$ = inductance, *in henrys*, of the field circuit, with open circuited armature. That is, the total field self-inductance. Not a *per-unit* quantity

$r$ = per-unit resistance of the armature circuit

$\mathcal{R}$ = resistance, *in ohms*, of field circuit. Not a per-unit quantity

$t$ = time, expressed as a fraction of the time corresponding to one radian at normal frequency. It is thus numerically equal to the elapsed radians

$x$ = armature reactance in general

$x_{ad}$ = three phase, line to neutral reactance of armature reaction, direct axis (See Appendix I)

$x_{ld}$ = three phase line to neutral armature leakage reactance, direct axis

$x_d = x_{ad} + x_{ld}$ = three phase, line to neutral synchronous reactance, direct axis

$x_d'$ = three phase line to neutral transient reactance, direct axis

$x_{AD}$ = static reactance single phase, corresponding to the space fundamental flux, direct axis. (See Appendix I)

$x_{LD}$ = single phase armature leakage reactance, direct axis

$x_D = x_{AD} + x_{LD}$ = total static reactance, single phase direct axis. (See Appendix I)

$x_D'$ = single phase static transient reactance, direct axis

The corresponding reactances in the quadrature axis are denoted by $q$ and $Q$, instead of $d$ and $D$.

$\alpha$ = displacement between armature winding axis and axis of field pole at the instant of short circuit. See Fig. 1

$\beta$ = angle between the axis of the short circuited winding and any open circuited winding considered

$\gamma$ = angle between armature winding axis and direct axis at any time $t$. See Fig. 1

$\phi_D$ = flux in the direct axis due to current in a single phase winding

$\phi_Q$ = corresponding flux in the quadrature axis

$\psi$ = flux linkages in the armature, in general

$\psi_i$ = flux linkages, produced in the armature by any transient armature current

$\psi_m$ = armature linkages due to current in the field winding

$\rho$ = ratio of open phase armature voltage to peak value of unit armature voltage

$\sigma_0$ = decrement factor of the field circuit, corresponding to the *total* self-inductance (*i. e.*, with armature open circuited). It is thus,

$$\sigma_0 = \frac{\mathcal{R}}{\omega\,\mathcal{L}_0}$$

where $\mathcal{R}$ is the total resistance (in ohms), $\mathcal{L}$ is the total inductance (in henrys), of the field circuit; and $\omega$ is the angular velocity corresponding to normal frequency—thus $2\,\pi\,f$.

Although, $\mathcal{R}$, $\mathcal{L}$, and $\omega$ are not *per-unit* quantities, $\sigma_0$ nevertheless is. The usual simple exponential is of the form

$\epsilon^{-\frac{t'}{t_0'}}$, where $t'$ and $t_0'$ are in seconds. In the present system $t$ represents the elapsed radians—*i. e.*, time is expressed as a fraction of the time of one radian at normal frequency. Thus, referring to the exponent

$$\frac{t'}{t_0'} = \frac{t'}{\mathcal{L}/\mathcal{R}} = \frac{\omega\, t'}{\omega\, \mathcal{L}/\mathcal{R}} = \sigma_0\, t$$

$\sigma_f$ = decrement factor of the field corresponding to the condition of single-phase short circuit. See equation (**2**)

$\sigma_a$ = corresponding decrement factor of the armature circuit. This factor is on a per-unit basis similar to $\sigma_0$. It is merely the ratio of per-unit $r$ to per-unit $x$. If these were each multiplied by unit ohms, and in the resulting ratio of resistance to reactance the factor $\omega$ were taken out of the reactance, the decrement factor would be back on the usual basis.

$\omega$ = $2\,\pi\, f$, where $f$ = normal frequency

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## Discussion

**C. H. Linder:** In *Synchronous Machines—Part IV*, mathematical relations are presented which permit the calculation of the short-circuit currents and voltages at the instant of single-phase short circuit, and at any time thereafter. Experimental data are included in the paper which check the calculated curves

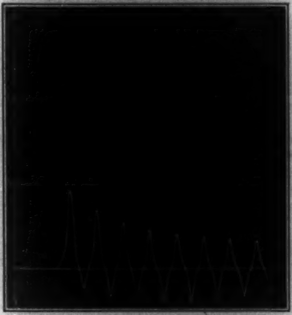


Fig. 1—Armature Current; the Short Circuit Occurring at the Instant of Maximum Linkages with the Short-Circuited Phase

Upper curve—Test
Lower curve—Calculation

Fig. 2—Field Current; the Short Circuit Occurring at the Instant of Maximum Linkages with the Short-Circuited Phase

Upper curve—Test
Lower curve—Calculation

accurately for both round-rotor and salient-pole machines at single-phase short circuit.

Additional evidence is presented in the accompanying Figs. 1 to 5, with particular reference to the correlation of test and calculated curves, for armature current, field current, and open-phase voltage, at single-phase short circuit on a salient-pole synchronous machine. The machine used to obtain the test data was rated: *A T I* 4-pole, 15-kv-a., 1800 rev. per min., 220 volts. All short circuits were made from line to line at a subnormal voltage, thereby eliminating any error in the test curves due to saturation. Open-phase voltages were measured 90 deg. from the short-circuited phase; for example, in case the short circuit was between line 2 and line 1, the open-phase voltage was measured from 3 to zero.

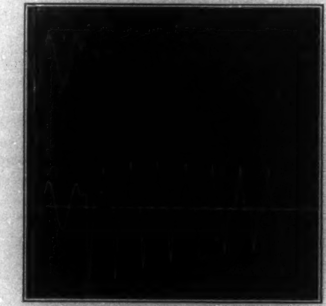


Fig. 3—Open-Phase Voltage; the Short Circuit Occurring at the Instant of Maximum Linkages with the Short-Circuited Phase

Upper curve—Test
Lower curve—Calculation

Fig. 4—Open-Circuit Voltage; the Short Circuit Occurring at the Instant of Maximum Flux Linkages with the Short-Circuited Phase

Upper curve—Without the amortisseur winding
Lower curve—With the amortisseur winding

A comparison of the curves shows that the open-circuit voltage is considerably less with than without the amortisseur winding; so that the amortisseur is beneficial in reducing open-phase voltages at single-phase short-circuit.

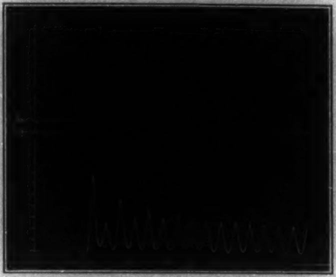


Fig. 5—Field Current; the Short Circuit Occurring at the Instant of Maximum Linkages in the Short-Circuited Phase

Upper curve—Without the amortisseur winding
Lower curve—With the amortisseur winding

The variation in field current is less with than without the amortisseur winding on the rotor. This is because the amortisseur winding acts as a cushion for the field, having induced in it a voltage which is otherwise induced in the field.

**B. A. Behrend:** Mr. Doherty has succeeded in elucidating one of the most important and intricate problems in a-c. circuits by a method of approach which makes a great appeal to the engineering mind. Simple and natural as it may seem it was an ingenious suggestion to treat the initial value of the short-circuit current of a synchronous or induction machine by assuming a circuit without resistance and introducing this resistance later to account for the decay of the short-circuit current. The general law which Mr. Doherty has developed and which he calls the "law of linkages" and for which he has given a general proof, is henceforth going to be a great help in solving engineering problems. In this present paper he has shown further how, by introducing a rather large number of factors, he is able to account in every detail, not only for the initial current, but also for the entire form of the decaying current wave. The striking agreement between his calculations and the records of the oscillograph are most interesting.

In actual practical calculations it may be advisable to sacrifice in completeness of calculation in order to gain in simplicity. The total errors involved may be no greater by pursuing such a course than by attempting to take into account every phase of the problem. However, much depends upon the taste of the individual designer and a method suited to one may not suit another.

**Robert Treat:** These papers on the reactance and behavior of synchronous machinery indicate that we are coming closer to a complete understanding of what goes inside of a synchronous machine. They do not indicate, to my mind, that we shall forever be burdened with the complication which a cursory examination of them would indicate. I believe that further study will show that for certain classes of calculations our solutions can be reduced to practically the same simplicity that they had years ago, but with this important difference; where before omissions were made because of our ignorance, in future they will be made because of our understanding that they have an insignificant effect on the result.

The operating engineer is interested in the internal processes of a synchronous machine from several standpoints. Among others, I might name three particularly important ones: first, from the standpoint of the duty which they are going to impose on oil circuit breakers; second, from the effect they are going to have upon the relaying system; and third, he is recently becoming interested in the effects which the synchronous machine is going to have upon the stability of his system; whether they are going to stay in synchronism with all their fellows on his system at all times or whether they are going to fall out of step sometimes, and if so, when, and under what conditions.

In respect to the first two, particularly, this is a function of the short-circuit current which will flow. The short-circuit current in the system is caused by a voltage and limited by an impedance. The voltage is generated by the synchronous machines. The impedance is furnished partly by these machines and partly by the external circuit.

In regard to the external circuit, we have for some time had a fair comprehension of the various characteristics which are important therein, of static apparatus in general, transmission lines, transformers, and so forth. But what went on inside has been a very considerable mystery. Not so very long ago oil circuit breakers were applied so far as interrupting capacity was concerned in terms of kilowatts installed in the station where the circuit breakers were put. A little later we distinguished between kv-a. supplied from salient-pole generators and from smooth-rotor generators. From that time we have progressed to a point where we now try to calculate as near as we know how the exact amount of current which the breakers may have to interrupt. It is a matter of considerable importance to an operator to know the amount of current which he is going to encounter on a short circuit in or near his power house. I mention only one effect. The electromagnetic stresses which he encounters in the bus supports and so forth vary not directly, but as the square of that current, hence, if his calculations of current are 50 per cent off, the results are over 100 per cent off.

The remarkable agreement reported by Messrs. Doherty and Nickle between their calculated and test results indicates that this mystery of what is going on inside the synchronous machine is disappearing. The results reported in these papers will be simplified, I am sure, so that they can be applied to a determination of what is going to happen in a system during transient disturbances and will, without any question, make the life of the operating engineers a little easier than it is now. If he can know how much short circuit is going to be encountered under all conditions with certainty, not only can his oil circuit breakers be determined with greater precision but, probably of more importance, he will be able to predict what his relay system is going to do under the various conditions to which it will be subjected.

**W. V. Lyon:** I should like first to congratulate the authors on the analysis they have made. However, I do not regard this analysis as the final word on this problem but only as a stepping stone to a more complete solution. For they, in order to make the solution come within our present mathematical ability, have neglected the losses in the circuit. That is, they have neglected them in determining the magnitudes of the currents and have later introduced them in order to obtain approximate values of the damping coefficients. This treatment seems to be quite satisfactory in the relatively simple problems that they have solved. Now it is a sure prediction that the mathematical difficulty which stands in our way to a more exact solution of the problem today will be removed tomorrow. One of the most promising ways of attacking transient problems is by means of the Heaviside operational method. It has proved of enormous value in solving problems dealing with static circuits and there seems to be no difficulty in extending the method to rotating machines. While speaking of mathematical difficulties it is interesting to point out that they are to a great extent removed if the d-c. exciting circuit is a polyphase one, for example, if the winding is arranged like a 3-phase symmetrical winding and has direct current supplied between one terminal and the other two terminals, which are themselves short-circuited. This system of excitation is assumed by Bekku in his recent analysis to which reference is made, see Fig. 6 herewith.

I do not wish to be understood as detracting in the least degree from the excellence of this paper but I must nevetheless emphasize that it should be regarded as a stepping stone to a more complete solution of the problem.

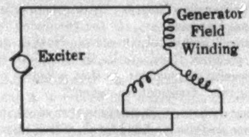
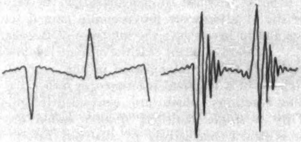


Fig. 6—Polyphase Excitation

There is one interesting point to which I should like to call attention. You will observe that in the oscillograms shown in Fig. 12 and Fig. 17 the first peak of current is highest, that the next two peaks are lower but are equal, that the next two are still lower but are also equal, whereas in the computed curve of current each peak is lower than the last. It would be interesting to know if the authors have any explanation of this.

I should like to point out that the nearest approach to a uniform air gap is in a properly designed induction motor. A rotor such as used in a turbo alternator does not have a uniform gap. Due to the effect of the slots which contain the field winding the reluctance of the air gap may be somewhat more in the quadrature axis than in the direct axis.

Although it is not particularly important, I believe it might avoid some confusion if the damping coefficients were not represented by the Greek "sigma," inasmuch as this letter is used to represent the leakage coefficient of two coupled circuits,[1] and is thus an important constant in both the steady-state and transient theory of such circuits. In fact, the so-called "transient reactance" which occurs in the solution of a polyphase short circuit of an alternator is the product of this leakage coefficient and the synchronous reactance, *i. e.*, in symbols, $X_t = \sigma X_s$ I suggest that, following a very common practise, the Greek "alpha" be used as the damping coefficient.[2]



7A 7B

Fig. 7—Effect of Condenser Load

I wish to comment on the high potential that is observed across the open phase under the condition of single-phase short circuit. Two years ago we obtained oscillographic records during a single-phase line-to-line short circuit when the generator was loaded with three condensers which were used to simulate a three-phase cable. We found that with the condensers used both the steady and transient potentials across the open phase were about 50 per cent greater than when the condensers were disconnected. The steady-state oscillogram of this potential without the condensers and with them are shown herewith in Figs. 7A and 7B. Another interesting and more common case is that in which the generator is connected to the line through transformers. Here the high potentials that would otherwise exist would be somewhat reduced due to the increased exciting current that a transformer takes when the applied potential is increased in this manner.

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[1] B. A. Behrend. Induction Motors.

[2] See Doherty and Shirley, *Reactance of Synchronous Machines and Its Applications*, Trans. A. I. E. E., 1918, Vol. XXXVII, p. 1248.

I feel very strongly about the use of the term "transient reactance." To speak of the "transient reactance" of a generator as has been done in the past is to my mind very unfortunate. Fundamentally reactance depends upon frequency, $x = 2\pi f L$ or in a more generalized form $x = p\,L$, where $p$ is the so-called generalized angular velocity. If the frequency is omitted the term "reactance" in general is useless. Now in this problem of alternator transients there are in the simplest case armature currents of several frequencies, so that a logical mind is forced to ask what is this "transient reactance"?

In analyzing some new phenomenon we often draw upon our past experience and use modified forms of well known terms with which to describe it, rather than invent new terms which will be distinctive. For example, the impedance of an a-c. circuit was called the apparent resistance and similarly, the product of the potential and current, $VI$, was called the apparent power. Now to anyone who is familiar with the simple theory of power in the a-c. circuit, it is apparent that the product $VI$ is *not* the power and this appellation of "apparent power" only befogs the understanding. When the first attempts were made to calculate the transient current in an alternator at short circuit the underlying theory was very imperfectly understood and, following precedent, it was perhaps natural that a crude method should be devised which contemplated dividing an electromotive force by a reactance, just as would be done in the problem of the steady-state short circuit.

If at this time we had been fortunate in having an exact analysis based upon reasonable assumptions, it is quite probable that the term "transient reactance" would not have come into general use, but that the transient currents would be computed in terms of resistance, self and mutual inductances, and the so-called leakage coefficients. We are now beginning to realize that the theory of these transient currents cannot be expressed by such a simple formula as was at first proposed. It is interesting to note that Messrs. Durgin and Whitehead who suggested this term, "transient reactance," in 1912 apparently appreciated the complexity of the problem more than many who have since attempted to apply their method. This is what they say:

"This paper is confined to demonstrating the existence of a characteristic of alternators provisionally named the *transient impedance* and to investigate the influence of the characteristic . . . . . it seems evident that the current is limited by some reactance beside those contemplated in the original theory[3]". "The existence of a transient reactance, or rather the existence of complex reactions which are conveniently grouped and replaced by a single fictitious quality called the transient reactance is shown conclusively by the test results and has, indeed, been more or less clearly appreciated for some time.[4]"

At first the "transient reactance" was taken to be the so-called leakage reactance of the armature, but this conception has gradually changed until it is, as the present authors show, taken to be what might be called the "equivalent reactance" of the armature and field windings. That is, it is the reactance measured on the armature side with the field winding short-circuited in the same way in which the equivalent reactance of a transformer or of an induction motor is measured. To quote from the paper by Messrs. Doherty and Shirley on *Reactance of Synchronous Machines and Its Applications.*[5] the value of the transient current at symmetrical polyphase short circuit is given by:

$$\sqrt{2}\left(\frac{E}{x_t} - \frac{E}{x_s}\right)\epsilon^{-\alpha_f t} + \sqrt{2}\,\frac{E}{x_t}\,\epsilon^{-\alpha_a t}.$$

This is still founded on the idea that the transient current is determined by dividing a generated e. m. f. by a "transient reactance." The symbol $E$ is rather indefinitely defined as "the voltage per leg," but it seems to be apparent that it represents the phase e. m. f. on open circuit. Let us apply this method of analysis to the following problem. An alternator operating in parallel with others loses its field excitation due to a break in the field circuit of the exciter. The field winding of the alternator is still closed through the armature of the exciter. Directly after the armature current of the alternator reaches its steady value, which may not be much in excess of its full-load value, a polyphase short circuit occurs at the terminals of the alternator. The problem is to determine the transient current in the alternator. We have here a case in which there is no e. m. f. due to field excitation and furthermore there is no steady short-circuit current. If the theory of transients is no more perfectly understood than is expressed by the above equation it would be said that the transient current is zero, whereas, as a matter of fact, it may be nearly as great as if the polyphase short circuit had occurred before the alternator lost its field excitation.[6] Obviously if this is true anything that fosters the idea that the transient current can be computed by dividing a generated e. m. f. by a "transient reactance" in a manner similar to that in which the steady current is determined, impedes our progress toward a true understanding of the problem. To the writer's mind the very term "transient reactance" does this by suggestion. Now while it is true that the problem of transient conditions in machinery is a complicated one at best it is also true that approximate solutions can be obtained which are at once relatively simple and accurate. In some of these approximate solutions it so happens that one of the important constants of the machine is what is commonly called the "equivalent reactance." This equivalent reactance is measured by applying potential to one of the windings and short circuiting the other, as is done, for example, in the case of a transformer or of an induction motor. It is now suggested that this same test be used in determining the so-called "transient reactance" of an alternator. It seems but logical that, if the same test procedure is followed in the case of a transformer, an induction motor, and an alternator, and the same use is made of the results of this test in solving steady and transient problems concerning the transformer and the induction motor and in solving transient problems concerning the alternator, this commonly determined constant of the machines should have a common name. If this constant has a certain designation in one case it should have the same designation in all cases. When discussing the transformer and induction motor the term "equivalent reactance" is used. This has come to have a definite and well understood significance. It certainly does not tend to clarify the understanding of the transient problem to call a similarly defined and measured constant of a synchronous machine by another name especially if this name itself suggests an erroneous conception of the problem. If the term, "equivalent reactance" is believed unsuitable for this commonly determined constant we should choose some other appropriate name, but let us at least be consistent in our nomenclature.

Furthermore I predict that as the operational method is extended to the problem of machine transients the terms that will be used will be resistance and self and mutual inductance. At present I can only hope that use of the term "transient reactance" will be as fleeting as its name implies.

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[3] "Transient Electric Phenomena and Oscillations," Steinmetz.

[4] "Transient Reactions in Alternators," by W. A. Durgin and R. H. Whitehead.

[5] Trans. A. I. E. E., 1918, Vol. XXXVII, p. 1209.

[6] The ratio of the transient currents in these two cases is the ratio of $E$ to $V$, *i. e.*, the ratio of the generated volts on open circuit in the first case to the terminal volts at the time that the short circuit occurs in the second case with no field excitation. This readily follows from the analysis given in the writer's paper, *Transient Conditions in Electric Machinery*, Trans. A. I. E. E., 1923, Vol. XLII, p. 157.

**W. F. Dawson:** It is out of the question to go through all of the detailed work indicated by these formulas as a preliminary to each design made, but when a group or line of machines is developed they naturally follow uniform proportions until they look more or less like brothers and behave as such. Of course no line is complete until there is reasonable assurance that detailed calculations of the "reactance" will indicate values approximately as required. After these mathematical investigations, the thought naturally arises, Why do we do it? What application shall we make of the results? It has already been stated it is to give the operators a chance to select their oil switches and to protect their systems. This apparatus is selected from the knowledge of the reactance and on the assumption that the oscillograph waves of short circuit current will be sinusoidal. This assumption is approximately true in the case of turbo alternators having solid fields, but with laminated fields on short circuit, the wave shapes are often contracted considerably at the base. This means that if the oil switches and other apparatus are selected on the basis of thermal capacity they will be larger than necessary.

What I consider as another error in the interpretation of oscillographs is the projection of the crest envelope to the instant of short circuit and assuming the maximum current to be the intersection point instead of the top of the first wave which occurs from ¼ to ½ cycle later and which is usually 10 to 15 per cent less than the intersection point. It is not the intersection point but the altitude of the maximum wave crest which determines the mechanical stresses.

It seems reasonable to expect the Standardizing Committee ultimately to take cognizance of these important details and that the selection of oil switches will depend upon the actual r. m. s. of the wave shape, so far as thermal capacity is concerned, and of the maximum altitude of the first wave so far as mechanical strength is concerned.

**H. M. Hobart:** To get curves to coincide as nicely as in Fig. 16 between the estimated and the observations by the oscillograms seems to me marvellous. Twenty years ago I never dreamed that any such command of the subject would have been possible. Any price is justifiable to have such a command of predetermination of these characteristics of dynamo-electrical machines.

The comparison given in Fig. 16 between the predetermined curve of the transient field current, and the curve actually obtained with the oscillographs, is extremely interesting and remarkable as proof of the great progress which has been made in obtaining a quantitative knowledge of these complicated occurrences.

**H. H. Spencer:** Messrs. Doherty and Nickle treat at considerable length decrement factors but their eq. (9) does not take any attenuation into account. I should like to ask if they will explain how these entered into the calculations of curve 11 or subsequent curves which show a very sharp decrement of successive peaks.

**R. E. Doherty:** If I have interpreted the discussion correctly, Mr. Behrend's impression is that the results, while apparently of an accurate nature, are nevertheless too complicated to be of much use. Now the *results* are really not complicated, even if some of the equations leading up to them are. For instance, the relations shown in Fig. 9 and in eqs. 9 to 15 inclusive do not appear so.

But suppose they are so considered, what is the justification? It certainly is not, as Mr. Behrend suggests, to exact the last per cent of accuracy in those problems which already may be solved within practical engineering accuracy. None of us wishes to increase the engineer's already heavy burden of numerical calculation. On the contrary, my own experience as a designer places me in sympathetic agreement with Mr. Behrend's appeal for simplicity in such matters, and I have spent many hours in affecting simplified calculations. But mere accuracy is not the objective here. Progress makes it necessary o answer new questions and calculate characteristics which have not been extensively dealt with. A sound theory, as indicated by the close agreement of test and calculation, makes it possible to answer such questions and to calculate such characteristics with some degree of confidence. And that is the justification for any relative complication which may appear in this work.

In stating that "damping" is of comparatively little importance, Mr. Behrend is probably right, in so far as he is considering only those results, such as mechanical force, which may depend on the first impulse. But in other connections, such as circuit-breaker ratings and synchronizing power following short circuits, damping is of very great importance.

Mr. Behrend mentioned the oscillograph. The function of this instrument is to record not merely the general shape, but also the magnitude. The short-circuit curves are accurately indicated by the oscillograph, and in the figures which are given in the paper the magnitude checks as well as the form. For much higher frequency—say 10,000 cycles per second—the ordinary oscillograph records would not be reliable, but they are for such phenomena as are shown here.

With reference to Mr. Dawson's remarks: I understand that his statement that "Everything is being based on the assumption that the wave shape is sinusoidal," refers to the usual interpretation of oscillograph records—such, for instance, as dividing the peak value of an off-set wave by 2 $\sqrt{2}$ to obtain the r. m. s. of the a-c. component. He is right that such a procedure is incorrect unless the wave is sinusoidal, and usually it is not. Relations between the peak current and other values are given in Appendix B.

However, I could hardly agree with his statement that the "theoretical value" at zero time "is no good." It may not be, for selecting oil switches, but there are other uses and reasons for knowing it. This matter is one of the major points of the companion paper by Park and Robertson.

Mr. Dawson's comments and predictions at the close of his discussion would have been in order 15 years ago; but I am not aware that anyone nowadays selects circuit breakers on the basis of the *initial* current, corresponding to what he terms the "theoretical reactance," *i. e.*, transient reactance. Many years ago standard decrement curves were adopted as a first step toward a rational method of selecting circuit breakers. We must keep the transient reactance, but we must use it properly in connection with decrement factors, etc., to obtain the desired result.

In reply to Mr. Spencer's question, the decrement factors are derived in Appendix H, and applied in Appendices B and C, under *Transient Currents.* Also the simplified forms of equations are given in Appendix A.

Unlike Mr. Behrend, Professor Lyon believes there are yet more details which should be included in the theory. In determining the magnitude of the initial currents, we have neglected resistance, and have made an approximation in taking it into account in the decrement factors. While the calculated results appear satisfactory, there is no question about the desirability of including all factors rigorously. As stated in the paper, no one has yet done it in the general case, but we hope and trust that Professor Lyon will be able to do this.

The slight variation of the test curves from calculated curves in Figs. 12 and 17 is due, as explained in the title of Fig. 17, to the fact that the magnetic linkages were not quite zero, as assumed when the short circuit occurred.

Professor Lyon feels strongly that the term "transient reactance" should be abandoned. Perhaps a better name could have been found when this term was first proposed, or even later in 1918 when I endorsed it after consulation with a number of interested engineers, including Dr. Steinmetz; but a more appropriate name did not appear. Nor has any since that time, in my opinion. Certainly "equivalent" reactance is not better. There are already too many "equivalent" things.

The term "transient reactance" is not illogical, inasmuch as it indicates the nature of the phenomena to which it is applicable. In this respect, it seems quite as logical as the term "synchronous reactance." Certainly, no one would interpret the latter to indicate that the reactance is, itself, "synchronous," but merely that it is the reactance which applies to certain conditions of synchronous operation, *i. e.*, steady-state conditions. Until a more significant and appropriate term than "transient reactance" is available, it would seem convenient and desirable to continue its usage.

With regard to the specific problem given by Professor Lyon, the solution in terms of open-circuit voltage, transient reactances, etc., is quite simple. Let

$i_0$ = armature current while the machine is connected to the bus.
$x_d'$ = transient reactance line to neutral.
$x_d$ = synchronous reactance line to neutral.

If the machine is removed from the bus and immediately short-circuited, the short-circuit current will be the same as if the short circuit occurred while the machine was still connected to the bus. When the machine is disconnected from the bus, the induced field current or nominal voltage is, as shown in *Synchronous Machines III*,

$$e_d = i_0 \, (x_d - x_d') \tag{1}$$

Since on open circuit, the nominal voltage is numerically equal to the terminal voltage, assuming no saturation,

$$E = i_0 \, (x_d - x_d') \tag{2}$$

Then when short circuit occurs

$$i = \frac{E}{x_d'} = i_0 \frac{(x_d - x_d')}{x_d'} \tag{3}$$

When the machine is connected to a bus of voltage, $E_1$, the current, $i_0$, is

$$i_0 = \frac{E_1}{x_d} \tag{4}$$

Then

$$i = \frac{E_1}{x_d'} - \frac{E_1}{x_d} \tag{5}$$

As pointed out in the discussion, this current may be nearly as large as if the machine were short-circuited at no load and at a voltage, $E_1$. The difference is merely the current which existed before short circuit.

# The Calculation of the Armature Reactance of Synchronous Machines

BY P. L. ALGER*

Member, A. I. E. E.

**Synopsis.**—*This paper presents new and simplified formulas for the armature leakage reactance of synchronous machines, and compares the results obtained with tests on 100 machines of varied types. The new formulas are characterized by novel expressions for the end leakage and for the "air-gap" or "differential leakage" reactances. Formulas for zero phase-sequence reactances are also given. The definitions of armature leakage and armature reaction reactances used are those proposed by Doherty and Nickle in 1926, and as a result the leakage reactance has a much smaller value than has heretofore been assigned to it, thus requiring a rather fundamental revision of the ordinary conceptions of the flux densities existing in the various parts of a loaded synchronous machine.*

## I. INTRODUCTION

THE growing interest of operating engineers in machine reactances, (as system stability and short-circuit phenomena become continually more important), together with the recent advances in the theory of synchronous machines, make renewed consideration of the subject of reactance calculation opportune at the present time. Papers on this subject have appeared in the JOURNAL'S pages at intervals over a period of more than 20 years, each paper marking a further refinement of methods and an advance in accuracy. At first, it was customary merely to estimate the numbers of leakage lines per ampere inch of embedded and free conductor, and multiply them by the respective lengths to obtain the reactance. Later, the reactance was segregated into several distinct elements that were separately calculated. These calculations due to their greater importance and in this case, the possibility of more accurate tests have reached greater precision in connection with induction machines than with synchronous machines. Adams[11,13,14] first developed formulas for induction motor reactances, and later Fechheimer[9] and Doherty and Shirley[7] developed formulas for synchronous machines. In 1926 Doherty and Nickle[3] presented some fundamental extensions of the theory of synchronous machines, and proposed new, more precise, definitions of armature leakage reactance and of armature reaction reactance. The present paper adopts these new definitions and develops simple formulas for the accurate calculation of the two quantities, for salient pole machines.

The reactance of armature reaction is here defined as the reactance due to the fundamental sine wave of air-gap flux produced by the armature current acting alone. It is calculated by means of the curves derived by Wieseman[2] from flux plots. There are two distinct values for it, the direct axis value occurring when the axis of armature m. m. f. coincides with the pole axis; and the quadrature axis value, occurring when the axis of armature m. m. f., is midway of the interpolar space.

The armature leakage reactance is defined as the difference between the total, or synchronous, armature reactance and the above defined reactance of armature reaction. The distinction between the leakage and the armature reaction components of the total reactance is quite an arbitrary one, since no winding can have a definite value of leakage reactance except with respect to another winding. Some distinction of this character is very desirable, however, for convenience in calculating the transient reactance, and for other purposes. The armature leakage reactance as above defined, is as nearly equal as may be, to that part of the total armature reactance which remains the same under transient as under steady conditions of operation.

Following Adams' treatment of the induction motor, the armature leakage reactance of a synchronous machine will be divided into four parts; the slot, end, zigzag, and belt leakages. Formulas for each of these will be derived in turn. As the slot leakage has been quite satisfactorily treated by Adams[11] already, the discussion of it here will be abbreviated as much as possible, consistent with the derivation of a little more exact formula, and its extension to apply to zero phase-sequence currents. None of the other three elements of the leakage has been adequately treated by previous writers, so they will be given more detailed consideration.

The four divisions of the reactance found useful for induction machines are followed for the two reasons that they fit in very well with the new conceptions of leakage reactance, and that their adoption will tend to unify the theory of the two types of machine. In particular, the total "air-gap leakage," due to harmonics of the air-gap flux, is segregated into the two parts called zigzag and belt leakage, respectively, in order to permit the effects of the independent variables, number of slots, and number of phase belts to be separately taken into account.

All previously published formulas for zigzag leakage have involved the consideration of overlapping primary and secondary teeth, and so have inadequately taken into account the effects of flux fringing in the air-gap, and have been inapplicable to synchronous machines. Also, older formulas for end leakage have been frankly empirical in nearly all cases. All new formula for these elements will be derived by considering the leakage flux to consist of revolving magnetic fields, divided into a fundamental and a series of harmonics. In each case, the coefficient of the resulting formula will be derived from theoretical considerations alone, and no empirical multipliers will be used to bring the results into agreement with practise, although simplifying assumptions will be freely made as the occasion demands.

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For numbered references see bibliography.

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Before proceeding to the derivation of the formulas, it is desirable to get clearly in mind the distinctions between the four elements of the leakage that have been specified. The end leakage reactance is due to the flux linking the end windings alone. The slot leakage comprises all of the flux crossing the slots due to the armature current, but does not include flux passing from tooth to tooth in the air-gap space. Evidently there is a slight error here, because the flux lines near the mouth of the slot do not pass straight across, but bulge outwards into the gap. The zigzag leakage comprises all of the space harmonics of the air-gap flux, due to the armature current in a one slot per pole per phase winding which induces fundamental frequency voltages in the armature. This includes the flux which crosses from tooth to tooth in the air-gap and interpolar spaces without actually reaching the field surface, and so takes up the leakage flux at the point at which the slot leakage left it. The belt leakage then comprises all the remaining fundamental frequency voltage producing space harmonics of the air-gap flux due to armature current. This last reactance is the additional reactance that an actual winding has above that which it would have if there were as many phases as slots per pole. Thus, the zigzag leakage reactance is due to the deviation of the armature m. m. f. wave from a sinusoid, caused by the limited number of slots, and the belt leakage reactance is due to the further deviation caused by the limited number of phases.

The belt and zigzag reactances together have been appropriately called[5] the "differential leakage," since they are due to the deviations of the armature m. m. f. from the ideal sine wave. They may also be called "air-gap leakage," since they represent the difference between the total and the armature reaction components of the fundamental frequency voltage producing air-gap flux. As the differential leakage reactance varies with the relative positions of the axes of the armature m. m. f. and the poles, the armature leakage reactance varies likewise, and has a slightly higher value in the quadrature than in the direct axis.[8]

Formerly, the air-gap flux due to the armature current was divided into two parts, that due to the armature reaction, and that due to "tooth tip leakage."[7] The armature reaction part was intended to represent the air-gap flux produced by the armature that links the field, but the determination of this flux was erroneously based on the linkages of the armature by the air-gap flux due to the field.[7] The remaining part of the total air-gap flux produced by the armature was then called tooth tip leakage. As the new definition of armature reaction includes most of this latter flux, we have abandoned the name "tooth tip" and called the small remaining part, the synchronous frequency voltage-producing harmonic fluxes, "differential leakage," as just described.

Bearing in mind these conceptions of the leakage reactances which we are going to calculate, we can now proceed to the derivation of the formulas. The four components of the reactance will be taken up in the order of their difficulty, and subsequently the results of their application to actual machines will be compared with tests.

## II. SLOT LEAKAGE REACTANCE

Only two-layer barrel-type armature windings in open slots will be considered in this paper, since the inferior electrical and manufacturing characteristics of single layer windings have reduced them to a place of only historical importance in polyphase a-c. machines of American manufacture.

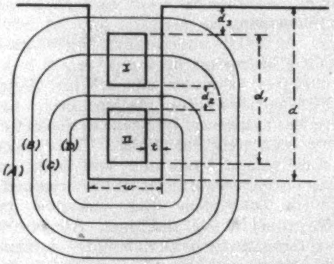


FIG. 1—SLOT LEAKAGE FLUX PATHS

Consider the slot shown in Fig. 1. All the flux crossing the slot returns below its closed end through a path of negligible reluctance, and none of it links any of the other slots. The leakage reactance in ohms per phase, due to this flux is then equal to the product of the following factors:

1. The permeance of the path across unit length of slot.
2. The embedded length of slot, or $L$
3. The number of slots in series per phase, or $S/q$
4. The square of the number of series connected conductors in each slot, or $\left(\frac{q\,Z}{S}\right)^2$
5. The rate of change of the flux, or $2\,\pi\,f$
6. A constant to reduce linkages per second to ohms, or $10^{-8}$

The permeance of the path for flux $A$ linking all the conductors in the slot of Fig. 1 is:

$$\frac{4\,\pi}{10}\left(\frac{d_3}{w}\right) \text{ lines per ampere per cm. length of slot}$$

And if the winding is full pitch, so that the currents in coil sides I and II are identical in magnitude and phase, the linkages per ampere produced by the flux in paths $B$ and $D$ are equal to the expression:

$$\frac{4\,\pi}{10}\left(\frac{d_1 - d_2}{3\,w}\right),$$

since with uniform current distribution over the height $d_1$, the flux density distribution is linear and the linkage distribution is parabolic, while the average height of a parabola is one-third its maximum height. As all the flux through path $C$ links one-half the total current, the linkages due to it are one-quarter as much as they would be if this flux linked all the current. The linkages due to $C$ are, therefore:

$$\frac{4\,\pi}{10}\left(\frac{d_2}{4\,w}\right),$$

and so the total slot reactance of a balanced, full pitch, polyphase winding is equal to:

$$X_{\text{slot}} = \frac{8\,\pi^2}{10^9}\,(f\,L)\,(S/q)\left(\frac{q\,Z}{S}\right)^2\left[\frac{12\,d_3 + 4\,d_1 - d_2}{12\,w}\right]$$

$$= \frac{0.79\,f\,L\,q\,Z^2}{10^7\,S}\left[\frac{12\,d_3 + 4\,d_1 - d_2}{12\,w}\right]$$

$$\text{ohms per phase} \qquad (1)$$

For dimensions measured in inches, the constant 0.79 becomes 2.006. The expression outside the bracket is a quantity containing factors common to many of the elements of reactance, and so it is convenient to give it a special symbol, $M$, in future equations. The bracketed expression is the "slot constant."

For a fractional pitch winding, the currents in the two coil sides in some slots are not in phase, and so, a more detailed analysis must be made. If the current in coil side II lags that in I by $\theta^0$, then in the slot carrying the return conductor of I, in the bottom of another slot, there will be (under balanced conditions) a top conductor carrying current $\theta^0$ ahead of the current in I. As the mutual inductance of I, with respect to II, is equal to that of II with respect to I, the out-of-phase component of voltage induced in each coil side by the other will be canceled by the corresponding out-of-phase voltage in the return coil side, leaving only the in-phase components of voltage to be considered.

The total self-inductance of I is proportional to:

$$\frac{1}{4}\left[d_3 + \frac{d_1 - d_2}{6}\right]$$

and that of II is proportional to:

$$\frac{1}{4}\left[d_3 + \frac{d_1 - d_2}{2} + d_2 + \frac{d_1 - d_2}{6}\right]$$

$$= \frac{1}{4}\left[d_3 + \frac{2\,d_1}{3} + \frac{d_2}{3}\right]$$

while their mutual inductance is proportional to:

$$\frac{1}{4}\left[d_3 + \frac{(d_1 - d_2)}{4}\right]$$

Hence, the total linkages due to the two currents $\theta^0$ out of phase acting together are proportional to:

$$\frac{1}{4}\left[d_3 + \frac{d_1 - d_2}{6}\right] + \frac{1}{4}\left[d_3 + \frac{2\,d_1}{3} + \frac{d_2}{3}\right] + \frac{(4\,d_3 + d_1 - d_2)\cos\theta}{8}$$

Or, the slot constant for this case is:

$$\frac{d_3}{2\,w}(1 + \cos\theta) + \frac{d_1}{24\,w}(5 + 3\cos\theta) - \frac{d_2}{24\,w}(3\cos\theta - 1).$$

When the winding pitch is 100 per cent, all the slots have $\theta = 0$ deg.; when the pitch is $\frac{q-1}{q}$, all the slots have $\theta = \frac{180 \text{ deg.}}{q}$, and when the pitch is $\frac{q-2}{q}$, they all have $\theta = \frac{360 \text{ deg.}}{q}$. For intermediate pitches, the slot constant varies linearly between these values. Thus, by plotting the function $K_S$ against per cent pitch, where $K_S$ is a broken line function having values equal to

$$K_S = \frac{1}{2}\left(1 + \cos\frac{m\,\pi}{q}\right) \text{ at } \frac{q - m}{q} \text{ pitch,} \qquad (2)$$

$m$ being any integer, (as shown in Fig. 2), and substituting it in the expression for the slot constant, we have as the final equation for slot reactance:

$$X_{\text{Slot}} = M\left[K_S\left(\frac{d_3}{w} + \frac{d_1}{3\,w}\right) + \frac{d_1}{12\,w}(1 - K_S) - \frac{d_2}{4\,w}\left(K_S - \frac{2}{3}\right)\right] \qquad (3)$$

The third term in this expression is negligible, except for zero phase-sequence currents, unless there is a large space between the top and bottom coil sides, as in the case of a multi-speed machine with two primary windings. The second term is very small, unless the pitch is below two-thirds, so that only the first term is ordinarily of importance.

The slot reactance given by (**3**), with the coefficients $K_S$ of Fig. 2, applies when balanced polyphase currents flow in the windings. It is sometimes desirable to know the slot reactance for other conditions, however, as for single-phase, or for zero phase-sequence currents. These reactances can all be obtained from equation (**3**), if proper values of $K_S$ are used. The appropriate values can readily be derived by the methods already employed, and therefore to save space the details of the work will be omitted here. The following table of special values of $K_S$ covers most of the cases that are met with in practise.

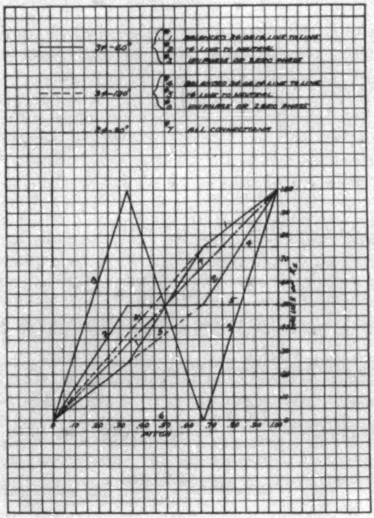


FIG. 2

It will be noted that the single-phase line to neutral slot reactance of a three-phase winding is not half the reactance between lines, unless the winding pitch is exactly 0, 50 per cent, or 100 per cent. This is so because the mutual slot reactance between any two phases, $A$ and $B$, is only zero when there are as many slots containing an $A$ coil side in the bottom and a $B$ in the top as there are slots containing a $B$ coil side in the bottom and an $A$ in the top; a condition that always exists with two-phase, but that only occurs with pitches of 0, 50, and 100 per cent with three-phase windings. As shown by Park,[1] the line to neutral reactance of a three-phase winding is always equal to two-thirds of the positive phase sequence reactance, plus one-third of the zero phase sequence reactance.

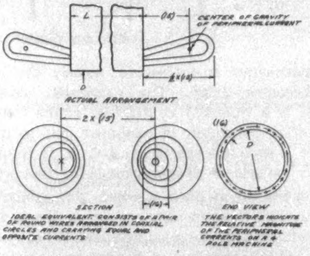
TABLE I
VALUES OF $K_S$ FOR USE IN EQUATION (3)

| Connection | Type of winding | Winding pitch 0 | 1/3 | 2/3 | 1 |
|---|---|---|---|---|---|
| | | $K_S$ values | | | |
| Balanced, three-phase | three-phase, 60-deg. belts | 0 | 0.250 | 0.750 | 1.00 |
| Line to neutral, one-phase | three-phase, 60-deg. belts | 0 | 0.500 | 0.500 | 1.00 |
| Line to line, one-phase | three-phase, 60-deg. belts | 0 | 0.250 | 0.750 | 1.00 |
| Zero phase | three-phase, 60-deg. belts | 0 | 1.00 | 0 | 1.00 |
| Balanced, three-phase | three-phase, 120-deg. belts | 0 | .375 | 0.750 | 0.750 |
| Line to neutral, one-phase | three-phase, 120-deg. belts | 0 | 0.250 | 0.500 | 0.500 |
| Line to line, one-phase | three-phase, 120-deg. belts | 0 | .375 | 0.750 | 0.750 |
| Zero phase | three-phase, 120-deg. belts | 0 | 0 | 0 | 0 |
| Balanced, two-phase | two-phase, 90-deg. belts | 0 | 0.333 | 0.667 | 1.00 |
| Line to line, one-phase | two-phase, 90-deg. belts | 0 | 0.333 | 0.667 | 1.00 |
| Zero phase | two-phase, 90-deg. belts | 0 | 0.333 | 0.667 | 1.00 |

For intermediate values of pitch, $K_S$ varies linearly between the tabulated values.

## III. END LEAKAGE REACTANCE

The leakage reactance of the end windings will here be considered as due to two kinds of field. The first kind is a revolving magnetic field of the same nature as those that are produced in the core length. This field flows in planes perpendicular to the shaft, and is due to the axially directed and winding currents only. Hereafter it will be designated as the "peripheral leakage field." The second kind is due to the peripherally directed end winding currents, shown in Fig. 4, which produce a leakage field flowing in radial planes, as indicated in Fig. 3. This will hereafter be called the "axial leakage field." The peripheral leakage predominates for synchronous machines with barrel type windings. With single layer chain type windings, the axial leakage flux is greatly increased, and so becomes the greater of the two. For induction machines, the peripheral leakage is greatly reduced by the proximity



IDEAL EQUIVALENT CONSISTS OF A PAIR OF ROUND WIRES ARRANGED IN COAXIAL CIRCLES AND CARRYING EQUAL AND OPPOSITE CURRENTS

THE VECTORS INDICATE THE RELATIVE MAGNITUDE OF THE PERIPHERAL CURRENTS ON A 4 POLE MACHINE

FIG. 3—AXIAL LEAKAGE FLUX OF END WINDINGS

of the primary and secondary windings, and so the axial leakage usually predominates.

The procedure will be, then, first to find the permeance of a cylindrical air core to a sinusoidally distributed encircling m. m. f., second to find the effective m. m. f. of this character produced by the end windings, third to determine thence the reactance due to the peripheral end leakage flux; and, finally, to determine the additional reactance due to the axial leakage. This completes the story for a salient-pole synchronous machine, where there is no mutual inductance between the armature and field end windings. For induction machines, however, the further step of subtracting the mutual reactance of the two windings from the sum of their total reactance is necessary.

As shown by earlier writers[3,6,10], the total flux per pole produced in a circular air core of one cm. axial length by a sinusoidal m. m. f. distributed around the periphery is equal to just twice the maximum m. m. f. in gilberts. Or:

$$\phi_1 = 2\left(\frac{4\,\pi\,A}{10}\right) \tag{4}$$

This equation assumes the flux to lie entirely in air on one side of the periphery of the core, and entirely in iron of high permeability on the other side. It makes no difference whether the air is on the inside or the outside of the core, and neither does it make any difference what the radius of the periphery of the core is. If there is no iron present, so the flux paths lie entirely in air, both inside and outside of the m. m. f., the reluctance is doubled, and so:

$$\phi_2 = \frac{4\,\pi\,A}{10} \tag{5}$$

The flux per pole produced by the same m. m. f. acting on a uniform air-gap of length $g$ is equal to:

$$\phi_3 = \frac{.8\,\pi\,A\,D}{g\,P} \tag{6}$$

And, therefore, the ratio of the flux produced by a given sinusoidally distributed m. m. f. acting on the periphery of an air cylinder of diameter $D$, with air outside, as well as inside the cylinder, to the flux produced by the same m. m. f. acting on a uniform air-gap of length $g$, is equal to:

$$\frac{\phi_2}{\phi_3} = \frac{P\,g}{2\,D}, \tag{7}$$

where $P$ is the number of poles of the m. m. f.

The magnetizing reactance due to the air-gap flux of an induction motor with uniform air-gap $g$ is equal to the product of the following factors:

1. The volts per phase due to unit flux per pole;
2. The flux per pole due to unit armature reaction;
3. The maximum of the sine wave of armature reaction per ampere in one phase.

The first of these factors is given by the familiar expression:

$$\frac{V}{\phi} = \frac{\pi}{\sqrt{2}}\,f\,K_p\,K_d\,Z\,10^{-8} \tag{8}$$

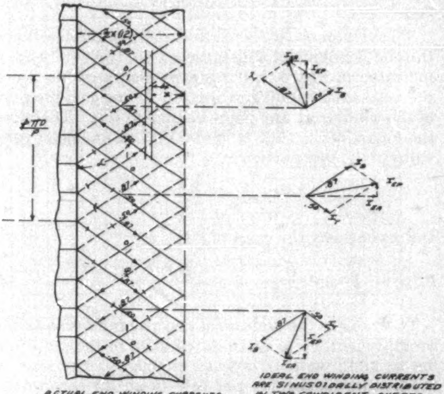
The second factor is:

$$\frac{\phi}{A} = \frac{8\,\pi\,D\,L}{10\,g\,P} \tag{9}$$

and the third* is:

$$\frac{A}{I} = \frac{2\,q\,Z\,K_p K_d}{\pi\,P\,\sqrt{2}} \tag{10}$$

The product of these three factors gives the magnetizing reactance of a polyphase armature winding in ohms per phase:



ACTUAL END WINDING CURRENTS FLOW IN EQUALLY SPACED BARS ARRANGED IN TWO LAYERS

IDEAL END WINDING CURRENTS ARE SINUSOIDALLY DISTRIBUTED IN TWO COINCIDENT SHEETS AND ARE ANALYZED AT EACH POINT INTO TWO COMPONENTS:- $I_{EP}$ PERIPHERALLY DIRECTED WHICH PRODUCES THE AXIAL LEAKAGE $X_{EA}$ AND $I_{EA}$ AXIALLY DIRECTED, WHICH PRODUCES THE PERIPHERAL LEAKAGE $X_{EP}$

FIG. 4—END WINDING CURRENT RELATIONSHIP

$$X_a = \frac{8\,\pi\,q\,f\,D\,L\,Z^2\,K_p\,K_d^2}{P^2\,g\,10^9}$$

$$= \frac{0.319\,K_p^2\,K_d^2\,D\,S\,M}{P^2\,g} \tag{11}$$

The ratio of the axial length of the end windings on both ends of the machine to the core length is:

$$\frac{\pi\,p\,D\tan\alpha}{P\,L}, \tag{12}$$

where $p$ is the fractional pitch, and $\alpha$ is the angle indicated in Fig. 4.

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*R. R. Lawrence, "Principles of Alternating-Current Machines," page 108.

Multiplying together (**7**), (**11**), and (**12**), the leakage reactance of the end windings due to the fundamental of the peripheral field only is:

$$X_{EP} = M\left[\frac{0.319\, K_d^2\, D\, S}{P^2\, g}\right]\left(\frac{P\, g}{2\, D}\right)$$

$$\left[\frac{\pi\, p\, D \tan \alpha}{P\, L}\right] F\,(p) = M\left[\frac{p\, D\, S\, K_d^2 \tan \alpha}{2\, P^2\, L}\right] F\,(p) \qquad (\mathbf{13})$$

where $F\,(p)$ is that function of the winding pitch that corresponds for the coil end projection length to the function $K_p^2$ over the core length. The distribution factor $K_d$ is the same for the end windings as for the core portion, due to the unvarying widths of the phase belts.

To evaluate $F\,(p)$, consider an elementary section of the end windings at a distance $x$ from the outer end, as indicated in Fig. 4. If $x$ is expressed as a fraction of the total axial winding projection on one end, the pitch of the winding at any point is equal to $p\, x$. Therefore, the square of the ratio of the m. m. f. at any point to its value in the core portion is,

$$\sin^2 \frac{p\, \pi\, x}{2},$$

and accordingly the value of $F\,(p)$ is:

$$F\,(p) = \int_0^1 \sin^2 \frac{p\, \pi\, x}{2}\, d\, x = \frac{p\, \pi - \sin p\, \pi}{2\, p\, \pi} \qquad (\mathbf{14})$$

To evaluate the additional end reactance due to the irregular peripheral space distribution of the end winding m. m. f., we may proceed as follows: The ratio of the $n$th harmonic flux per pole in an air core to the fundamental flux per pole is $n$ times greater than the same ratio for a uniform air-gap, (from equations (**5**) and (**6**) ). For a full pitch winding with a large number of slots per pole, the reactance due to the $n$th harmonic is therefore approximately $1/n^2$ times that due to the fundamental for an air core, and $1/n^4$ times the fundamental for a uniform air-gap, the latter ratio being derived in the section of this paper on belt leakage. The sum of the values of $1/n^2$ for all the harmonics present in a full-pitch polyphase winding with an infinite number of slots is equal to $1/K_d^2$.† The actual effect of the harmonics is less than this for windings with pitches a little less than 100 per cent, and greater for very short pitch windings, but these errors are not important. The tooth harmonics due to the concentration of the m. m. f. in a small number of conductors are smaller in the end windings than in the core, since the finite slot depth makes the actual length of flux path much greater for the higher harmonics than in the ideal case, for which the formulas are derived, where the m. m. f. is concentrated in a cylinder of zero thickness. Thus, the increase in end leakage reactance due to harmonics may be approximately taken care of by simply omitting the factor $K_d^2$ in the first member of equation (**13**).

The component of end leakage reactance due to axial flux may be evaluated by considering the peripheral components of the end winding currents at any fractional distance $x$ from the outer end of the winding, as indicated in Fig. 4. The peripheral currents in the upper and lower layers of the winding are out of phase in time by an angle equal to $p\, \pi\, x$, which differs by $\pi$ from the phase difference between the axially directed components of the same currents. Thus, the resultant peripheral current at any point is proportional to $\cos \dfrac{p\, \pi\, x}{2}$. The center of gravity of this current area is accordingly located at a distance from the end of the core equal to:

$$\frac{\pi\, p\, D \tan \alpha}{2\, P}\left[1 - \frac{\displaystyle\int_0^1 x \cos \frac{p\ \pi\ x}{6}\, dx}{\displaystyle\int_0^1 \cos \frac{p\ \pi\ x}{2}\, dx}\right]$$

$$= \frac{\pi\, p\, D \tan \alpha}{2\, P}\left(\frac{2 \tan p\, \pi/4}{p\, \pi}\right)$$

$$= \frac{\pi\, p\, D \tan \alpha}{4\, P}\left(1 + \frac{p^2}{5}\right) \quad \text{approx.} \qquad (\mathbf{15})$$

We will now make the assumption that the axial end leakage reactance is the same as if the peripheral current were concentrated in a conductor of circular cross-section at each end of the machine at the distance from the core ends given by (**15**). The proper diameter of cross section to assume for these conductors is evidently greater than the depth of primary slot, and less than the axial length of the end projection on one end. For reasons of simplicity, we will assume this diameter to be one-half the axial projection at each end, or, from (**12**):

$$\frac{\pi\, p\, D \tan \alpha}{4\, P} \qquad (\mathbf{16})$$

As the peripheral current extends over a radial depth equal to the depth of primary slot, the equivalent diameter cannot be less than this. Hence (**16**) is really based on the assumption that the primary slot depth is about equal to one-third the axial end projection, and if wide variations from this relationship occur, then (**16**) will be correspondingly in error. The effect of this error is to make the calculated reactance too high for very deep primary slots and too low for very shallow slots. However, since only the logarithm of this effective diameter enters the final equation, a considerable error in the diameter makes only a small error in the result.

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†Silberstein, "Synopsis of Applicable Mathematics," p. 87.

The current in this conductor varies cyclically around the periphery, its r. m. s. value for a full-pitch winding being $\frac{1}{2\sqrt{2}}$ times the total axially directed current in one pole pitch, or:

$$I_{EP} = \left(\frac{1}{2\sqrt{2}}\right)\left(\frac{K_p\,K_d\,q\,I\,Z}{P}\right)\left(\frac{2\sqrt{2}}{\pi}\right)$$

$$= \frac{q\,I\,Z\,K_p\,K_d}{P\,\pi} \qquad \textbf{(17)}$$

We will neglect the leakage flux that enters the ends of the armature core in an axial direction, as it is largely canceled by opposing eddy currents in the punchings, that are entered broadside on. Then, the peripheral currents at the two ends may be considered as flowing in a pair of parallel wires separated by a distance twice that given by (**15**).

Assuming the air-gap diameter, $D$, large compared with this distance, the problem reduces to that of calculating the reactive kv-a. of a single-phase transmission line consisting of round wires of a diameter given by (**16**), separated by a distance twice that given by (**15**), of a length $\pi\,D$, and carrying a current per conductor given by (**17**). The inductance of such a line is equal to:

$$\frac{2\,\pi\,D}{10^9}\left[\frac{1}{2} + 2\,l\,n\,4\,(1 + p^2/5)\right]\text{henrys}$$

which is practically equal to:

$$\frac{4\,\pi\,D\,(8.2 + p^2)}{(5)\,10^9} \qquad \textbf{(18)}$$

The total reactive volt-amperes due to the axial end leakage flux are, therefore, equal to:

$$X_{EA} = \frac{13.1\,f\,q\,D\,K_p^2\,K_d^2\,Z^2\,(1 + 0.12\,p^2)}{10^9\,P^2} \qquad \textbf{(19)}$$

Adding (**19**) to (**13**), and dropping the $K_d^2$ factor of (**13**) as previously explained, we obtain for the total end leakage reactance:

$$X_{End} = M\left[\frac{p\,D\,S\tan\alpha\,F\,(p)}{2\,P^2\,L} + \frac{K_p^2\,K_d^2\,D\,S\,(1 + 0.12\,p^2)}{6\,P^2\,L}\right] \qquad \textbf{(20)}$$

We will take $\alpha$ = 60 deg., a value higher than the usual angle of the ends, but one that checks the mean length of conductor on most windings, and so one that allows something for the straight portion beyond the core. Equation (**20**) then reduces to:

$$X_{End} = \frac{0.3\,M\,D\,S\,(3\,p - 1)}{P^2\,L}$$

very closely. The substitution of 0.3 $(3\,p - 1)$ for the complicated function of pitch given in (**20**) is justified by the comparison of the two values shown in Fig. 5. Over the ordinary range of pitches from 0.5 to 1.2, the agreement is very satisfactory. We will, therefore, adopt (**21**) as our final expression for the end leakage reactance of a synchronous machine with a barrel-type primary winding.

Equation (**21**) gives the end leakage reactance, under the condition of balanced polyphase currents flowing in the armature winding. As the derivation of this equation is based on the assumption that the end leakage fields are due to revolving m. m. fs., with nearly negligible space harmonics, the reactances for other winding connections may be taken as proportional to the corresponding values of armature reaction.

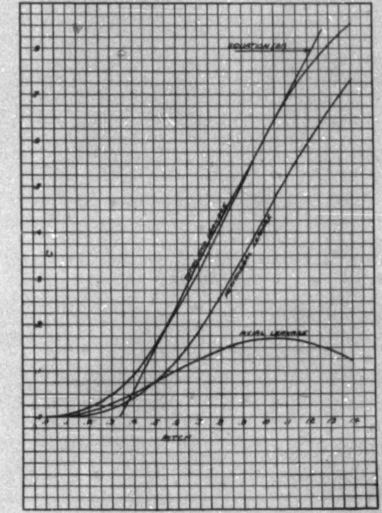

FIG. 5—END LEAKAGE REACTANCE COEFFICIENTS

On this basis, the coefficient 0.3 of equation (**21**) may be changed in accordance with the following table in the special connection cases:

TABLE II

| Connection | Winding | Value of coefficient for equation (21) |
|---|---|---|
| Balanced polyphase....... | two or three-phase | 0.3 |
| Single-phase, line to neutral | two or three-phase | 0.2 |
| Single-phase, line-to-line... | two or three-phase | 0.3 |
| Zero phase............... | three-phase, 60 or 120 deg.................. | 0 |
| Zero phase............... | two-phase | 0.3 |

### IV. ZIGZAG LEAKAGE REACTANCE

Inasmuch as the stator windings of polyphase machines consist of coils arranged in a finite number of slots and connected in a finite number of phases, usually two or three, the shape of the wave of magnetomotive force along the air-gap surface is not sinusoidal, even though the winding carries balanced sinusoidal polyphase currents. At any particular instant the shape of the m. m. f. wave is stepped, the agreement between the stepped figure and a true sinusoid becoming closer and closer as the numbers of slots and phases are made larger and larger, until perfect agreement results when both the number of slots and the number of phases are infinite.

As shown in reference 3, the air-gap flux produced by this stepped m. m. f. wave in a salient-pole synchronous machine consists of three elements:

1. A fundamental sine wave stationary on the rotor, inducing fundamental frequency voltages;
2. A series of harmonics moving with respect to the rotor and also inducing fundamental frequency voltages; and
3. Other harmonics inducing other than fundamental frequency voltages in the armature winding.

Of these, 1 is the effect of the armature reaction, 2 constitutes an element of the leakage reactance, and 3 may be disregarded. Thus, if we now derive a formula for 2, we will complete the work of determining the armature leakage reactance.

In the present discussion, to begin with, an ideal type of machine will be considered. The air-gap length will be assumed uniform, and the flux will be assumed to cross the gap radially. The slots will be assumed to have no real physical existence which might entail a variation in air-gap permeance, but will be assumed to be merely the points along the periphery of the machine at which the current is concentrated and at which, therefore, the m. m. f. changes. Under these conditions, the air-gap flux will vary along the periphery of the machine at any instant in a stepped wave shape exactly proportional to the m. m. f. at each point.

If the flux wave produced by the stator currents alone be considered, it has been shown that the stepped wave of flux may be analyzed into a fundamental sinusoidal distribution of flux having the same number of poles as that for which the stator winding is connected, plus an infinite number of harmonic flux waves having different numbers of poles.[3] There being no rotor currents by assumption, the magnitudes of the fundamental, and of all of the harmonic fields, are proportional to the current in the windings, the back e. m. f. produced by these fluxes in the stator winding is proportional to the current, and the fluxes are truly self-inductive.

The reactance due to these harmonic fields constitutes the "air-gap leakage," or "differential leakage" reactance of the machine, which is usually divided into two parts, the "belt leakage" and the "zigzag leakage."

The distinction between belt leakage and zigzag leakage is that the former is due to the concentration of the m. m. f. in a definite number of phase belts, while the latter is due to its concentration in a definite number of slots. No accurate dividing line can be drawn between the two kinds of leakage, as they are mutually dependent on each other, and as in the case of one slot per pole per phase, for example, they coalesce into the same thing. The reason for making a distinction is that, for ordinary design proportions, a change in the number of slots affects only the zigzag leakage, while a change in the winding pitch affects only the belt leakage, so that the independent effects of number of slots and of pitch can be more easily dealt with when the two parts are considered separately.

Independent formulas will be developed for the belt and zigzag reactances, therefore, but it must be recognized that, whenever the number of slots per pole is small, the two are not separable, and the formulas become inaccurate. The only accurate way to obtain the total differential reactance is to compute it for each case separately, and tabulate the results. The computation of the total for any regular winding can be simply carried out by the means suggested by Chapman.[8] This has been done in Appendix A, wherein tables for some of the more usual regular windings are given.

The definitions adopted will be as follows:

The per cent differential leakage reactance is the total per cent reactance due to harmonic fluxes crossing the air-gap that are not of the fundamental number of poles. Or, it is the total excess per cent reactance, due to air-gap fluxes, above that of a similar machine, with an infinite number of slots and of phases.

The per cent belt leakage reactance is the total excess per cent differential leakage reactance of a polyphase armature winding above that of a squirrel-cage winding with the same number of slots.

The per cent zigzag leakage reactance is the total per cent differential leakage reactance of a squirrel-cage winding, or of a winding with as many phases as it has slots per pole.

In this section we will consider the zigzag leakage, or the harmonic fluxes produced by a squirrel-cage winding. It is shown in Appendix A by Chapman's method that the total inductance of a full pitch winding with one slot per pole per phase, as a ratio to the inductance of one full-pitch coil is:

$$Q = \frac{1}{s} \csc^2 \frac{\pi}{2s}, \tag{22}$$

where $s$ is the number of slots per pole.

And, it is also shown in Appendix A that the total useful inductance of such a winding, due to the fundamental flux it produces, as a ratio to the inductance of one full pitch coil is:

$$Q_u = \frac{4s}{\pi^2} \tag{23}$$

Hence, the zigzag leakage, $X_t$, is equal to:

$$X_t = X_a \left( \frac{\pi^2}{4\, s^2} \csc^2 \pi/2\, s - 1 \right) \qquad (24)$$

where $X_a$ is given by (**11**).

As $\pi/2\, s$ is a small angle, (**24**) may be developed into a series of which only the first two terms need be considered, so that:

$$X_t = \frac{\pi^2 X_a}{12\, s^2} \left( 1 + \frac{\pi^2}{20\, s^2} + \frac{\pi^4}{504\ \ s^4} + \ldots \right) \qquad (25)$$

or, approximately:

$$X_t = \frac{5\, X_a}{6\, s^2} = \frac{5}{6} \left( \frac{P^2}{S^2} \right) X_a \qquad (26)$$

Equation (**26**), then, gives the desired result, the total differential leakage reactance of a regular winding with one slot per pole per phase, or, by definition, the zigzag reactance of any winding with the same number of slots per pole. Clearly the error in the formula is small for large values of $s$, but it makes the calculated value a little low when $s$ becomes less than 3. The value of $X_t$ thus found applies to a single winding, and to the case of a uniform air-gap length.

For the case of a salient pole synchronous machine, the zigzag leakage can be found from the same formulas if an equivalent uniform value of air-gap length can be ascertained. It has been shown by Doherty and Nickle[3] that the reactance due to the $n$th harmonic of primary m. m. f. depends on the average permeance, and on the second harmonic of permeance variation only, and that these two permeances have different values for each harmonic. The effect of the variation of permeance due to the salient poles is to make the fundamental armature flux and the belt leakage flux greater in the main axis than in the quadrature axis, but to make the zigzag harmonic leakage fluxes greater in the quadrature axis than in the main axis. This is true because the predominating portions of the high order harmonic fluxes are produced at the points of maximum armature current, and these come over the pole faces (low reluctance) when the poles are in the quadrature axis, while they come over the interpolar spaces (high reluctance) when the poles are in the main axis.

The average permeance increases with the order of the harmonic, since the shorter the harmonic pole pitch, the greater the relative permeance for the peripheral flux that reenters the primary iron without ever reaching the pole face. For the same reason, the second harmonic of the permeance variation is less the greater the value of $n$.

The same authors have shown that the fundamental magnetizing reactance in the direct axis is proportional to:

$$K_{p_1}^2 K_{d_1}^2 ( p_0^{\mathrm{I}} + 1/2\, p_2^{\mathrm{I}} ),$$

and that on the same basis the direct axis magnetizing reactance for the $n$th harmonic is proportional to:

$$\frac{K_{p_n} K_{d_n}}{n} \left( \frac{K_{p_n} K_{d_n}}{n} p_0^{\mathrm{N}} + 1/2 \left( \frac{K_{p_{n \pm 2}} K_{d_{n \pm 2}}}{n \pm 2} \right) p_2^{\mathrm{N}} \right)$$

where the plus signs are taken if the $n$th harmonic rotates backwards with respect to the fundamental, and vice versa. For the quadrature axis, the signs of the $p_2$ terms in both the fundamental and the harmonic magnetizing reactance expressions change sign.

It may easily be shown that the product $K_{p_n} K_{p_{n \pm 2}}$ is always either negative or very small, and that $K_{d_n} K_{d_{n \pm 2}}$ is always negative for the low order (belt leakage) harmonics, but is positive for the tooth (zigzag leakage) harmonics. Hence, the numerical values of the two terms in the foregoing expression are additive for the belt leakage, but are subtractive for the zigzag leakage, and the contrary is true for the quadrature axis.

It is quite feasible to carry through the indicated numerical work for any particular case, using these general methods, but to do so for the general case is quite impractical. We will, therefore, make some bold assumptions at this point, with the object of obtaining a simple formula accurate enough for general use. First, we will assume average values for the permeance coefficients, corresponding to a two-thirds ratio of pole arc to pole pitch, a minimum air-gap two per cent of the pole pitch, and a maximum air gap 1.5 times the minimum, as follows:

$P_2^{\mathrm{I}} = 2/3\ p_0^{\mathrm{I}}$, $p_0^{\mathrm{N}} = 1.2\ p_0^{\mathrm{I}}$, and $p_2^{\mathrm{N}} = 1/3\ p_0^{\mathrm{N}}$.

On this basis, the $n$th harmonic magnetizing reactance varies about 15 per cent, above and below its average, between the direct and quadrature axes. We shall leave this relatively small variation out of account, therefore, and calculate only the average reactance, assuming it to be the same in both axes. Then, the ratio of the magnetizing reactance for the $n$th harmonic to the direct axis magnetizing reactance of the fundamental is approximately equal to:

$$\frac{X_{a_n}}{X_{a_d}} = \frac{.9\, K_{p_n}^2 K_{d_n}^2}{n^2 K_{p_1}^2 K_{d_1}^2}$$

Finally, we must take into account the fact that our ideal assumption of true rectangular m. m. f. waves for each coil is not exact. Actually, the m. m. f. of each slot is distributed across the slot opening, instead of concentrated at a point in the center of the slot, and so the steps in the m. m. f. waves are not vertical, but slightly sloping. This reduces all the harmonics appreciably, especially the higher order ones. We shall assume that the average effect of this error is to reduce the magnetizing reactance to 5/6 of its ideal value. Multiplying the last expression by this factor, therefore, we find the proper average value of $X_a$ to substitute in equation (**26**) is:

$$X_a = \frac{3}{4} X_{a_d} \qquad (27)$$

## V. Belt Leakage Reactance

The belt leakage reactance is due to the increase in differential leakage caused by reducing the number of phase belts per pole, $q$, to a small number. When the number of slots per pole is very large, this effect can be readily calculated, but as the slots are made fewer, the belt leakage increases to two or three times its limiting value. When the slots finally become equal to one per pole per phase, the belt leakage becomes zero, by definition. As the effect of the number of slots is further complicated by variations in the winding pitch, it is not considered practicable to present any adequate formula for the belt leakage in the general case. However, as the belt leakage is small by comparison with the zigzag leakage, unless $s$ is large, and as in this case the belt leakage formula is fairly accurate, these errors are not important. For accurate results, it is necessary to compute the total differential leakage reactance, and tabulate the results for all useful windings, as outlined in Appendix A.

This is especially necessary in the case of fractional slots per pole, as here the belt leakage increases greatly, and as it varies considerably, depending on the particular sequence of large and small numbers of slots per phase belt employed.

The harmonic fields corresponding to the belt leakage are of lower orders than those of the zigzag leakage, as the former are primarily due to the phase belts which extend over several of the slots to which the latter are due. Further, since all the harmonic fields must create fundamental frequency voltages in the producing winding, and since the $n$th harmonic has $n$ times the fundamental number of poles, it follows that each harmonic must revolve with respect to the producing winding at one $n$th of fundamental speed. Therefore, the harmonic fields due to the primary winding induce high frequency voltages in the secondary, and, if the latter is short-circuited, produce damping currents in it. A regular phase winding, or a salient-pole field winding, has so little admittance for these voltages that this damping effect can be neglected. But, in the case of a squirrel-cage, the induced currents are sufficient to greatly reduce the belt leakage harmonic fluxes. The zigzag leakage fluxes are only slightly reduced in usual cases, as the squirrel-cage admittance for these high order harmonics is small.

Therefore, the primary belt leakage can be practically neglected in all machines with integral slots per pole per phase, having squirrel-cage secondary windings, and so we will assume for this case:

$$X_B = 0 \tag{28}$$

For regular windings with an infinite number of slots per pole, the belt leakage reactance is the sum of the magnetizing reactances of all the harmonic m. m. fs. For synchronous machines the stator only need be considered, while for induction machines the stator and rotor belt leakage must be added to obtain the total.

As a first step, it will be necessary to calculate the ratio $\frac{X_{a_n}}{X_a}$, where $X_{a_n}$ is the magnetizing reactance of the $n$th harmonic. A measure of the effectiveness of the stator winding in producing fundamental flux is the number of turns in series per phase times the pitch and distribution factors for the fundamental number of poles, or:

$$N_1 = K_{p_1} K_{d_1} N$$

in the same way the effectiveness of the stator winding in producing $n$th harmonic flux is measured by

$$N_n = K_{p_n} K_{d_n} N,$$

where $K_{p_n}$ $K_{d_n}$ are the pitch and distribution factors, respectively, of the stator winding for the $n$th harmonic flux.

If a voltage is applied to the primary winding and is first assumed to be opposed entirely by fundamental flux and then entirely by $n$th harmonic flux, the ratio of the magnetizing currents in the two cases will be the ratio of $X_{a_n}$ to $X_a$.

If $\phi$ is the total flux per pole, then

$$\phi_n = \phi_1 \frac{N_1}{N_n},$$

and if $B$ is the air-gap flux density, then

$$B_n = B_1 \frac{N_1}{N_n},$$

since the area of each pole for the $n$th harmonic is $1/n$ times that for the fundamental.

Since for the $n$th harmonic there are $n$ times as many poles to magnetize as there are for the fundamental, the magnetizing current in the second case is:

$$I_{m_n} = I_{m_1} \frac{N_1^2}{N_n^2} n^2$$

And, as the magnetizing reactance is equal to the ratio of the applied voltage to the magnetizing current, the per cent $n$th harmonic magnetizing reactance is:

$$\% X_{a_n} = \frac{1}{n^2} \left( \frac{K_{p_n}^2 K_{d_n}^2}{K_{p_1}^2 K_{d_1}^2} \right) \tag{29}$$

The total belt leakage reactance is equal to the sum of the magnetizing reactances of all the harmonics existing with a definite number of phases, a definite winding pitch, and an infinite number of slots. It is well known that a winding with $q$ phase belts per pole produces only those harmonics whose orders are equal to $2\,k\,q \pm 1$. And, for all these harmonics, the distribution factor with an infinite number of slots is simply equal to one $n$th of the fundamental distribution factor. Hence, we may write:

$$X_B = X_a \sum^{n=\infty} \frac{K_{p_n}^2}{n^4 K_{p_1}^2}, \tag{30}$$

where $n$ takes only the values $2\,k\,q \pm 1$; $k = 1, 2, 3, \ldots$

For a full pitch two-phase winding with 90 deg. phase belts, this is:

$$X_{B_{90}} = X_a \left( \frac{1}{3^4} + \frac{1}{5^4} + \frac{1}{7^4} + \ldots \right)$$

$$= \left( \frac{\pi^4}{96} - 1 \right) X_a = 0.0147\, X_a \tag{31}$$

For a full-pitch three-phase winding with 60 deg. phase belts, it is:

$$X_{B_{60}} = X_a \left( \frac{1}{5^4} + \frac{1}{7^4} + \frac{1}{11^4} + \frac{1}{13^4} + \ldots \right)$$

$$= (1 + X_{B_{90}}) \left( 1 - \frac{1}{3^4} \right) - X_a = \left( \frac{5\,\pi^4}{486} - 1 \right) X_a$$

$$= 0.00214\, X_a \tag{32}$$

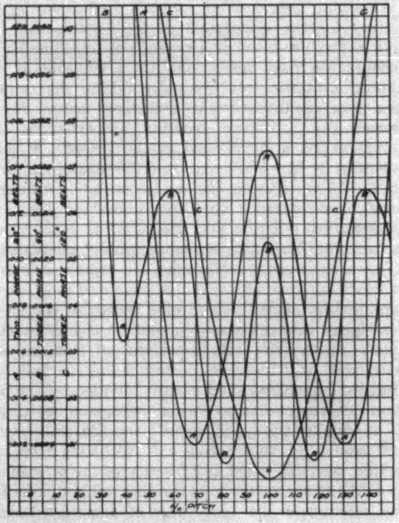

Fig. 6—Chart of Values of $K_B$ the Belt Leakage Constant

For a full-pitch three-phase winding with 120 deg. phase belts, it is also 0.00214 $X_a$, but in this case it increases rapidly as the pitch changes from unity, due to the resulting dissymmetry of the winding, while in the other cases $X_B$ decreases as the pitch changes from unity.

The actual value of $X_B$ for any pitch for each type of winding can not be expressed by any simple formula, but must be found by actually carrying out the summation indicated in (**30**). This has been done, and the results are shown in Fig. 6.

The value of $X_B$ for a salient pole synchronous machine is also approximately given by the foregoing equation, if 3/4 the direct axis magnetizing reactance is used for $X_a$, as shown in the previous section. Summing up, therefore, the belt leakage reactance is equal to:

$$X_B = 0 \tag{28}$$

for any machine with a squirrel-cage winding and integral slots per pole per phase;

$$X_B = \frac{3}{4} X_{ad}\,(K_{B_1}) \tag{33}$$

for salient-pole synchronous machine without squirrel-cage; and with integral slots per pole per phase; and

$$X_B = X_T = \frac{5}{8} \left( \frac{P^2}{S^2} \right) X_{ad} \tag{34}$$

for a salient-pole synchronous machine with fractional slots per pole per phase. This last equation is arbitrary, as $X_B$ for fractional slot windings varies very widely, but in a general way $X_B$ in such cases is larger the larger $X_T$ is, and it is on the average of the same order of magnitude. From some unpublished work of Professor A. A. Bennett, the differential leakage reactance for six different fractional slot windings averaged 1.82 times $X_T$. Hence, our assumption of 2 for this factor in the general case is not unreasonable, and should be satisfactory until such time as an adequate table of differential leakage reactance values for irregular windings is available.

Since some of the harmonics of belt leakage flux for fractional slot windings are of fractional, and many are of rather low, orders, a squirrel-cage winding will have demagnetizing currents induced in it, which may reduce the belt leakage reactance considerably. The magnitude of this effect is extremely variable, however, as it depends on many factors. It is the writer's opinion that the demagnetizing action of a squirrel-cage on the belt leakage reactance due to fractional slot windings is small for usual design proportions, and so it will be neglected in the present paper.

In these equations, we have derived expressions for all the elements of the reactance, and we may now turn to their application to actual machines.

## VI. APPLICATION TO SALIENT POLE SYNCHRONOUS MACHINES

The leakage reactance in ohms of a salient pole synchronous machine with integral slots per pole, and with a squirrel-cage winding, has been determined by (**3**), (**21**), (**26**), (**27**), and (**28**), to be:

$$X_1 = M \left[ K_s \left( \frac{d_3}{w} + \frac{d_1}{3\,w} \right) + \frac{0.3\,(3\,p - 1)\,D\,S}{P^2\,L} \right]$$

$$+\frac{5}{8}\left(\frac{P}{S}\right)^2 X_{ad} \qquad (35)$$

The belt leakage given by equation (**33**) or (**34**) should be added in case the machine has fractional slots or has no squirrel-cage winding. The second order terms of the slot reactance (equation (**3**)) have been omitted as being non-essential for normal synchronous machines.

Expressed as a fractional voltage drop due to full-load current, (**34**) becomes by (**8**), (**10**), and (**11**):

$$X_1 = \frac{7.90\,A}{K_p^2\,K_d^2\,\phi}\left[\frac{P\,L\,K_S}{S}\left(\frac{d_3}{w}+\frac{d_1}{3\,w}\right) + \frac{0.3\,(3\,p-1)\,D}{P}\right] + \frac{5}{8}\left(\frac{P}{S}\right)^2\left(\frac{A\,K_a}{F}\right) \qquad (36)$$

for lengths measured in cm., the constant 7.90 becoming 20.0 if inch units are used. The value of $F$ to be used in the last term of (**36**) is the number of normal voltage field ampere-turns, and $K_a$ is the constant required to convert armature reaction ampere-turns into equivalent field ampere-turns. $K_a$ depends on the particular shape of field pole and length of air-gap used, but it has an average value a little less than 0.9, and is given by Fig. 7.

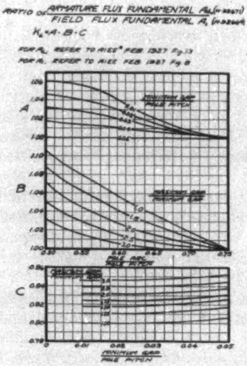

Fig. 7

A further simplification of (**36**) can be made by putting $K_S = \frac{3\,p+1}{4}$, which is exactly correct for three-phase windings with pitches between 2/3 and 1, and which is slightly higher than correct for all other windings, (Fig. 2). As two-phase windings have higher belt leakages, and as the neglected second order terms in the slot reactance become appreciable when the pitch is below 2/3, the small errors so introduced are on the right side.

Finally, therefore, our formula for the per cent leakage reactance, expressed as a decimal, of a salient-pole synchronous machine with a barrel-type armature winding, and fractional slots per pole, in inch units, is:

$$X_1 = \frac{20\,A}{K_p^2\,K_d^2\,\phi}\left[\frac{P\;L}{S}\left(\frac{3p+1}{4}\right)\left(\frac{d_3}{w}+\frac{d_1}{3\,w}\right) + \frac{0.3\,(3\,p-1)\,D}{P}\right] + \frac{1.1\,A}{F}\left((P/S)^2 + 0.6\,K_B\right) \qquad (37)$$

If integral slots per pole are used, the $(P/S)^2$ term should be multiplied by 0.5 If in addition the machine has a squirrel-cage winding, the $K_B$ term is to be omitted. The reactance is assumed to be the same in both axes, but actually it is greater in the quadrature axis than in the direct axis by about 1/4 of the $A/F$ term.

As the value of $X_1$ found from test is totally different, depending on how the armature reaction is converted into equivalent field ampere-turns, it is necessary to consider the matter before proceeding to the comparison of test reactances with those given by (**37**).

Wieseman[2] has derived accurate coefficients by flux plotting for the calculation of the fundamental sine wave of flux produced in a salient pole machine by the concentrated field turns, and by a sinusoidally distributed armature reaction. By taking the ratio of these two coefficients, the necessary factor, $K_a$, to convert the armature reaction ampere-turns into equivalent field ampere-turns, can be derived. This has been done by Mr. Wieseman, and the result is shown in Fig. 7. By substituting the quadrature axis coefficients, also given in reference No. 2, for those of the direct axis, the armature reaction and the total, or synchronous, reactance in either axis can be accurately calculated.

The usual way to determine the armature leakage reactance by test is first to take open and short-circuit characteristic curves, which give armature voltage on open-circuit and armature current on sustained short circuit, respectively, as functions of field current. Then, the field current corresponding to full load armature current on short circuit, divided by the field current corresponding to normal voltage on the air-gap line, is equal to the synchronous reactance, expressed as a fraction. By subtracting the calculated armature reaction, also expressed as a fraction of the no load air-gap field ampere-turns, from the test value of synchronous reactance, the test value of armature leakage reactance is found. The calculated armature reaction ampere-turns are given by (**10**), multiplied by the value of $K_a$ from Fig. 7.

As the errors of the test value of synchronous reactance probably average one per cent, and as Fig. 7 also involves slight errors, it is evident that this method of obtaining the leakage reactance is inherently very inaccurate. On high-speed machines, the leakage reactance is very small by comparison with the total reactance, so that the results are particularly inaccurate in this case.

It is possible to measure the total leakage reactance of a synchronous machine at standstill, just as for an induction machine, but this requires the inclusion of the reactances of the field winding and squirrel-cage, if present, which do not enter the calculation of steady state performance. It is also possible to measure the armature reactance with the rotor removed and to determine the leakage reactance as the difference between the total and the calculated reactance due to the fundamental of the flux produced in the air core. This last method involves large errors in the amounts of zigzag and end leakage, however, and is not as accurate as the usual short circuit test method of measurement. Finally, it is possible to insert exploring coils on the armature surface and by their means measure the net flux existing during a short-circuit test, which gives a measure of the leakage reactance. The dissymmetry and wave form errors introduced, unless the exploring coils exactly follow the armature coil grouping, together with the fact that the slot leakage part of this flux links only a portion of the winding, make this method of no practical use. For these reasons, the usual method of finding $X_1$ from open and short-circuit tests has been followed in checking the results obtained with the formulas derived in this paper.

TABLE III
HIGH SPEED MACHINES

| Poles | Kv-a. | Freq. | Calculated | | | Test | Test $X_d$ |
|---|---|---|---|---|---|---|---|
| | | | $X_{ld}$ | $X_{ad}$ | $X_d$ | $X_d$ | Calc. $X_d$ |
| 4 | 80 | 60 | 0.105 | 0.955 | 1.060 | 1.043 | 0.984 |
| 4 | 105 | 50 | 0.054 | 1.220 | 1.274 | 1.250 | 0.981 |
| 4 | 180 | 60 | 0.061 | 1.002 | 1.063 | 1.032 | 0.971 |
| 4 | 600 | 60 | 0.060 | 2.163 | 2.223 | 2.195 | 0.987 |
| 4 | 940 | 25 | 0.128 | 1.770 | 1.898 | 1.895 | 0.998 |
| 4 | 2000 | 25 | 0.198 | 1.562 | 1.762 | 1.793 | 1.018 |
| 4 | 3000 | 25 | 0.117 | 2.300 | 2.417 | 2.355 | 0.974 |
| 4 | 5700 | 25 | 0.109 | 1.857 | 1.966 | 1.937 | 0.980 |
| 6 | 150 | 25 | 0.102 | 1.040 | 1.142 | 1.092 | 0.954 |
| 6 | 187 | 60 | 0.063 | 0.998 | 1.061 | 1.068 | 1.007 |
| 6 | 200 | 60 | 0.055 | 0.804 | 0.859 | 0.872 | 1.015 |
| 6 | 400 | 60 | 0.069 | 1.250 | 1.319 | 1.275 | 0.967 |
| 6 | 435 | 60 | 0.077 | 1.127 | 1.204 | 1.172 | 0.973 |
| 6 | 500 | 60 | 0.151 | 2.065 | 2.216 | 2.212 | 0.998 |
| 6 | 500 | 60 | 0.105 | 1.610 | 1.715 | 1.678 | 0.978 |
| 6 | 1000 | 60 | 0.127 | 1.932 | 2.059 | 2.040 | 0.991 |
| 6 | 1500 | 60 | 0.092 | 2.025 | 2.117 | 2.145 | 1.013 |
| 6 | 3125 | 25 | 0.098 | 1.019 | 1.117 | 1.133 | 1.014 |
| 6 | 5000 | 25 | 0.097 | 1.060 | 1.157 | 1.161 | 1.003 |
| 6 | 5000 | 25 | 0.088 | 1.592 | 1.680 | 1.745 | 1.039 |
| | | | Average | | | | 0.999 |
| | | | Average error from mean | | | | ±0.017 |
| | | | Average error from 1 | | | | ±0.012 |

TABLE IV
MEDIUM HIGH SPEED MACHINES

| Poles | Kv-a. | Freq. | Calculated | | | Test | Test $X_d$ |
|---|---|---|---|---|---|---|---|
| | | | $X_{ld}$ | $X_{ad}$ | $X_d$ | $X_d$ | Calc. $X_d$ |
| 8 | 560 | 60 | 0.067 | 0.815 | 0.882 | 0.884 | 1.002 |
| 8 | 800 | 60 | 0.077 | 1.338 | 1.415 | 1.416 | 1.001 |
| 8 | 1200 | 60 | 0.086 | 1.073 | 1.159 | 1.150 | 0.992 |
| 8 | 2500 | 60 | 0.143 | 2.100 | 2.243 | 2.230 | 0.994 |
| 8 | 5000 | 60 | 0.161 | 1.750 | 1.911 | 1.928 | 1.009 |
| 10 | 1100 | 60 | 0.097 | 0.983 | 1.080 | 1.098 | 1.019 |
| 10 | 1880 | 60 | 0.061 | 1.139 | 1.200 | 1.214 | 1.012 |
| 10 | 7500 | 60 | 0.080 | 0.853 | 0.933 | 0.922 | 0.988 |
| 12 | 1000 | 25 | 0.081 | 0.810 | 0.891 | 0.905 | 1.016 |
| 12 | 1900 | 25 | 0.089 | 0.758 | 0.847 | 0.842 | 0.994 |
| 12 | 2400 | 60 | 0.159 | 1.103 | 1.262 | 1.245 | 0.986 |
| 12 | 2500 | 60 | 0.093 | 1.452 | 1.545 | 1.564 | 1.012 |
| 12 | 5000 | 60 | 0.132 | 1.560 | 1.692 | 1.667 | 0.985 |
| 12 | 5000 | 60 | 0.101 | 0.750 | 0.851 | 0.852 | 1.001 |
| 12 | 5300 | 60 | 0.135 | 1.280 | 1.415 | 1.414 | 0.999 |
| 12 | 7000 | 50 | 0.115 | 0.900 | 1.015 | 0.987 | 0.972 |
| 12 | 12500 | 50 | 0.110 | 1.048 | 1.158 | 1.172 | 1.012 |
| 12 | 15000 | 60 | 0.086 | 0.667 | 0.753 | 0.766 | 1.017 |
| 12 | 15000 | 60 | 0.137 | 1.065 | 1.202 | 1.208 | 1.005 |
| 16 | 3500 | 50 | 0.114 | 0.969 | 1.083 | 1.071 | 0.989 |
| | | | Average | | | | 1.000 |
| | | | Average error from mean | | | | ±0.010 |
| | | | Average error from 1 | | | | ±0.010 |

TABLE V
MEDIUM LOW-SPEED MACHINES

| Poles | Kv-a. | Freq. | Calculated | | | Test | Test $X_d$ |
|---|---|---|---|---|---|---|---|
| | | | $X_{ld}$ | $X_{ad}$ | $X_d$ | $X_d$ | Calc. $X_d$ |
| 18 | 1,650 | 40 | 0.108 | 0.844 | 0.952 | 0.993 | 1.043 |
| 18 | 1,650 | 60 | 0.123 | 0.961 | 1.084 | 1.100 | 1.015 |
| 20 | 2,250 | 40 | 0.148 | 0.975 | 1.123 | 1.136 | 1.011 |
| 20 | 14,444 | 50 | 0.123 | 0.896 | 1.019 | 1.023 | 1.004 |
| 22 | 2,000 | 60 | 0.123 | 1.078 | 1.201 | 1.188 | 0.989 |
| 22 | 7,900 | 60 | 0.162 | 1.017 | 1.179 | 1.198 | 1.016 |
| 24 | 1,100 | 60 | 0.132 | 0.992 | 1.124 | 1.152 | 1.025 |
| 24 | 4,000 | 50 | 0.136 | 1.027 | 1.163 | 1.178 | 1.013 |
| 24 | 6,880 | 50 | 0.131 | 0.688 | 0.819 | 0.826 | 1.009 |
| 24 | 10,700 | 50 | 0.120 | 0.648 | 0.768 | 0.761 | 0.991 |
| 24 | 30,000 | 60 | 0.128 | 0.647 | 0.775 | 0.803 | 1.036 |
| 28 | 10,125 | 60 | 0.147 | 0.919 | 1.066 | 1.089 | 1.022 |
| 30 | 3,125 | 60 | 0.106 | 0.973 | 1.079 | 1.080 | 1.001 |
| 32 | 750 | 60 | 0.138 | 0.820 | 0.958 | 0.951 | 0.993 |
| 32 | 2,250 | 40 | 0.180 | 0.918 | 1.098 | 1.113 | 1.014 |
| 32 | 9,375 | 60 | 0.142 | 1.064 | 1.206 | 1.202 | 0.997 |
| 36 | 500 | 60 | 0.155 | 0.853 | 1.008 | 1.003 | 0.995 |
| 36 | 1,500 | 60 | 0.117 | 0.881 | 0.998 | 0.988 | 0.990 |
| 40 | 750 | 60 | 0.162 | 0.756 | 0.918 | 0.906 | 0.987 |
| 40 | 1,375 | 60 | 0.088 | 0.619 | 0.707 | 0.716 | 1.013 |
| | | | Average | | | | 1.008 |
| | | | Average error from mean | | | | ±0.013 |
| | | | Average error from 1 | | | | ±0.014 |

In Tables III to VII inclusive, the calculated and test values of synchronous reactance are compared for five groups of machines of different types. The machines were selected at random, and the tests were all made in the regular commercial routine. The average absolute error for the entire list of 100 machines is 0.4 per cent, and the average numerical error is 1.7 per cent, so that the results are as accurate as could reasonably be expected when the errors of test and those inherent in Fig. 7 are considered. If the value of the armature reaction reactance, $X_{ad}$, and the test value of total reactance, $X_d$, are assumed to be exact, the test value of leakage reactance can be found by subtracting the one from the other. This has been done for each group of machines, and the average errors between the test and calculated values of $X_l$ for each case are given in Table VIII, together with the corresponding errors in $X_d$.

The average absolute error of the leakage reactance for the 100 machines on this basis is 0.6 per cent, and the average numerical error is 14.6 per cent. The worst errors occur for the high speed machines, and inspection of Table VIII indicates that the calculated value of $X_d$ is appreciably too high for high speed machines and a little too low for low speed machines. By empirical adjustments of the coefficients of the end and differential leakage components of the reactance, it is evident that these errors could be reduced. Such adjustments of the constants should be made by each manufacturer for himself, however, as they will depend upon the particular end winding constructions, and so forth, that each one uses. The formulas as given were derived straightforwardly from theoretical considerations, and no attempt has been made to make empirical corrections, although simplifying assumptions have been freely used.

TABLE VI
LOW SPEED MACHINES

| Poles | Kv-a. | Freq. | Calculated $X_{ld}$ | Calculated $X_{ad}$ | Calculated $X_d$ | Test $X_d$ | Test $X_d$ / Calc. $X_d$ |
|---|---|---|---|---|---|---|---|
| 56 | 3,500 | 60 | 0.144 | 0.798 | 0.942 | 0.960 | 1.019 |
| 56 | 4,500 | 60 | 0.147 | 0.860 | 1.007 | 1.013 | 1.006 |
| 56 | 5,720 | 60 | 0.159 | 0.648 | 0.807 | 0.775 | 0.960 |
| 60 | 750 | 60 | 0.177 | 0.699 | 0.876 | 0.902 | 1.030 |
| 60 | 1,500 | 60 | 0.155 | 0.871 | 1.026 | 1.041 | 1.015 |
| 60 | 1,500 | 60 | 0.231 | 0.587 | 0.818 | 0.882 | 1.078 |
| 60 | 2,500 | 60 | 0.130 | 0.724 | 0.854 | 0.849 | 0.994 |
| 64 | 625 | 60 | 0.168 | 0.782 | 0.950 | 0.907 | 0.955 |
| 64 | 6,250 | 60 | 0.128 | 0.870 | 0.998 | 1.013 | 1.015 |
| 64 | 8,000 | 60 | 0.254 | 0.776 | 1.030 | 1.043 | 1.013 |
| 68 | 1,500 | 60 | 0.192 | 0.766 | 0.958 | 0.961 | 1.003 |
| 72 | 750 | 60 | 0.239 | 0.818 | 1.057 | 1.065 | 1.008 |
| 72 | 875 | 60 | 0.223 | 0.818 | 1.041 | 1.068 | 1.026 |
| 72 | 1,000 | 60 | 0.228 | 0.740 | 0.968 | 0.962 | 0.994 |
| 72 | 2,250 | 60 | 0.147 | 0.813 | 0.960 | 0.983 | 1.024 |
| 72 | 12,250 | 60 | 0.213 | 0.782 | 0.995 | 1.015 | 1.020 |
| 72 | 32,500 | 60 | 0.166 | 0.926 | 1.092 | 1.130 | 1.035 |
| 80 | 3,500 | 60 | 0.187 | 0.810 | 0.997 | 1.020 | 1.023 |
| 82 | 2,250 | 60 | 0.162 | 0.745 | 0.907 | 0.898 | 0.990 |
| 100 | 1,250 | 60 | 0.127 | 0.510 | 0.637 | 0.652 | 1.024 |
| | | | Average | | | | 1.011 |
| | | | Average error from mean | | | | ±0.018 |
| | | | Average error from 1 | | | | ±0.022 |

TABLE VII
SMALL LOW SPEED MACHINES

| Poles | Kv-a. | Freq. | Calculated $X_{ld}$ | Calculated $X_{ad}$ | Calculated $X_d$ | $X_d$ | Test $X_d$ / Calc. $X_d$ |
|---|---|---|---|---|---|---|---|
| oe | 200 | 60 | 0.249 | 0.970 | 1.219 | 1.228 | 1.007 |
| 36 | 240 | 60 | 0.244 | 0.833 | 1.077 | 1.076 | 1.001 |
| 40 | 80 | 60 | 0.281 | 0.660 | 0.941 | 0.962 | 1.022 |
| 44 | 62 | 60 | 0.284 | 0.576 | 0.860 | 0.888 | 1.033 |
| 36 | 100 | 60 | 0.302 | 0.704 | 1.006 | 1.008 | 1.002 |
| 80 | 120 | 60 | 0.245 | 0.793 | 1.038 | 1.017 | 0.980 |
| 40 | 360 | 60 | 0.208 | 1.013 | 1.221 | 1.256 | 1.029 |
| 42 | 160 | 60 | 0.293 | 0.961 | 1.254 | 1.307 | 1.042 |
| 44 | 50 | 60 | 0.430 | 0.972 | 1.402 | 1.460 | 1.041 |
| 44 | 62 | 60 | 0.251 | 0.619 | 0.870 | 0.906 | 1.041 |
| 44 | 62.5 | 60 | 0.143 | 0.417 | 0.560 | 0.552 | 0.986 |
| 46 | 100 | 60 | 0.277 | 0.698 | 0.975 | 0.965 | 1.010 |
| 50 | 145 | 60 | 0.171 | 0.476 | 0.647 | 0.648 | 1.002 |
| 52 | 140 | 60 | 0.207 | 0.611 | 0.818 | 0.838 | 1.024 |
| 60 | 60 | 60 | 0.108 | 0.301 | 0.409 | 0.404 | 0.988 |
| 60 | 250 | 50 | 0.151 | 0.612 | 0.763 | 0.771 | 1.010 |
| 60 | 250 | 60 | 0.290 | 0.902 | 1.192 | 1.183 | 0.992 |
| 62 | 280 | 60 | 0.195 | 0.657 | 0.852 | 0.826 | 0.969 |
| 72 | 165 | 60 | 0.196 | 0.519 | 0.715 | 0.729 | 1.020 |
| 74 | 375 | 50 | 0.224 | 0.781 | 1.015 | 1.005 | 1.010 |
| | | | Average | | | | 1.010 |
| | | | Average error from mean | | | | ±0.017 |
| | | | Average error from 1 | | | | ±0.019 |

The causes for the varying magnitudes of error shown in Table VIII are brought out more clearly by a study of the relative proportions of the various elements of the total reactance for the different types of machines. Table IX gives the average ratios of slot, end, and differential leakage to the total leakage reactance; and also the average ratio of the total leakage reactance to the armature reaction reactance for each case. Since in the high-speed machines, $X_l$ averages only 6 per cent of $X_d$, while in the small low-speed machines it averages 25 per cent, it is clear that a given error in the measurement of $X_l$ makes more than four times as great an apparent error in $X_l$ in the former as in the latter case. This partially accounts for the relatively large numerical errors in $X_l$ for high-speed machines.

TABLE VIII

| Type of machine | Test / Calc. | Per cent Absolute error | Per cent Numerical error From 1 | Per cent Numerical error From mean |
|---|---|---|---|---|
| Errors in values of $X_l$ | | | | |
| High-speed (II) | 0.86 | −13.6 | 31 | 30 |
| Medium high-speed (III) | 1.01 | 1.0 | 11 | 11 |
| Medium low-speed (IV) | 1.06 | 6.3 | 11 | 10 |
| Low-speed (V) | 1.06 | 5.7 | 12 | 10 |
| Small low-speed (VI) | 1.04 | 3.6 | 8 | 7 |
| Errors in values of $X_d$ | | | | |
| High-speed (II) | 0.992 | − 0.8 | 1.9 | 1.7 |
| Medium high-speed (III) | 1.000 | 0.0 | 1.0 | 1.0 |
| Medium low-speed (IV) | 1.008 | 0.8 | 1.4 | 1.3 |
| Low-speed (V) | 1.011 | 1.1 | 2.2 | 1.8 |
| Small low-speed (VI) | 1.019 | 1.0 | 1.9 | 1.7 |

TABLE IX

| Type of machine | Average ratios $\frac{X_{Slot}}{X_l}$ | $\frac{X_{End}}{X_l}$ | $\frac{X_{Dif}}{X_l}$ | $\frac{X_l}{X_d}$ | $\frac{X_{l\,new}}{X_{l\,old}}$ |
|---|---|---|---|---|---|
| High-speed | 0.37 | 0.60 | 0.03 | 0.059 | 0.56 |
| Medium high-speed | 0.57 | 0.35 | 0.08 | 0.087 | 0.58 |
| Medium low-speed | 0.60 | 0.32 | 0.08 | 0.132 | 0.66 |
| Low-speed | 0.67 | 0.16 | 0.17 | 0.189 | 0.70 |
| Small low-speed | 0.58 | 0.16 | 0.26 | 0.252 | 0.72 |

The last column of Table IX gives the average ratio of the new value of leakage reactance, to the value given by the older formulas derived by Doherty and Shirley.[7] This ratio varies from a little over one-half for the high speed, to nearly three-quarters for the low-speed machines. The percentage error between test and calculated values of $X_l$ is thus magnified on the new basis, so that a direct comparison of the accuracy given by the two formulas cannot be made. The older formula had an average apparent error of about 16 per cent, so that taking into account the test errors, which cause a considerable part of the dispersion, the new formula is indicated to have about half the true error of the old.

## VII. Zero Phase-Sequence Reactance Calculations

The zero phase reactance is important in the calculation of single phase short circuits, circulating currents in delta windings, and in other cases. The slot portion of this reactance is given by the complete equation (**3**), using the appropriate values of $K_S$ from Fig. 2. For usual three-phase windings, $K_S$ for the zero phase sequence reactance is equal to $3\,p - 2$. The end leakage portion is very small, and will be neglected. The differential leakage portion is given by the ratio of equation (**12a**) or (**13a**) to (**14a**) in Appendix A. Combining these expressions, we derive the following formula for the zero phase reactance of a three-phase, 60 deg. belt winding, with a pitch between 2/3 and unity, expressed as a decimal:

$$X_{\text{zero phase}} = \frac{20\,A}{K_p^2\,K_d^2\,\phi}\left(\frac{P\,L}{w\,S}\right)$$

$$\left[(3\,p-2)\,(d_3) + (9\,p-5)\,\frac{d_1}{12} - (9\,p-8)\,\frac{d_2}{12}\right]$$

$$+\ \frac{4\,A\,K_0\,(p-2/3)}{F\,K_p^2\,K_d^2}$$

$$\left[\left(\frac{P}{S}\right)^2 + \frac{1}{27} + 7/18\,(p-2/3) - (p-2/3)^2\right] \quad (\mathbf{38})$$

The corresponding formula for a winding pitch between 1/3 and 2/3 is:

$$X_{\text{zero phase}} = \frac{20\,A}{K_p^2\,K_d^2\,\phi}\left(\frac{P\,L}{w\,S}\right)$$

$$\left[(2-3\,p)\,d_3 + (7-9\,p)\,\frac{d_1}{12} - (4-9\,p)\,\frac{d_2}{12}\right]$$

$$+\ \frac{4\,A\,K_0\,(2/3-p)}{F\,K_p^2\,K_d^2}$$

$$\left[\left(\frac{P}{S}\right)^2 + \frac{1}{2}\,(2/3-p) - (2/3-p)^2\right] \quad (\mathbf{39})$$

The coefficient $K_0$ is introduced in (**38**) and (**39**) to allow for the reduction of the harmonic fluxes, especially the third, by induced currents in the rotor circuits. As all the terms except the first in the last brackets of these equations represent third harmonic fluxes, these terms are generally reduced to a fraction of their apparent values, and $K_0$ should ordinarily be taken as less than 0.5. The coefficient 4 of the last bracket in (**38**) includes the factor of 3/4 for the average permeance of a salient pole machine, as previously derived.

The zero phase reactance has been calculated for two machines, and the values compared with tests, with the following results:

| Poles | Kv-a. | Freq. | Winding pitch | Assumed value of $K_0$ | Zero-phase Sequence Reactance | | |
|---|---|---|---|---|---|---|---|
| | | | | | Calculated | Test | Per cent error |
| 6 | 435 | 60 | 2/3 | | 0.026 | 0.021 | −24 |
| 36 | 20,000 | 60 | 0.80 | 0.25 | 0.070 | 0.0675 | 4 |

## VIII. Conclusions

It is believed that equation (**37**) is at once the most accurate and the simplest comprehensive formula for the armature leakage reactance of a synchronous machine that has been published. It requires no curves, no logarithms, and no tables for its use, but only a few slide rule operations, and it gives a value of leakage reactance which, added to the armature reaction reactance derived from flux plots, quite accurately checks the test values of synchronous reactance for the entire range of salient pole synchronous machines in commercial use.

The leakage reactance so determined averages about two-thirds of that given by the widely used formulas derived in reference No. 7, since the latter included as leakage reactance a part of the fundamental sine wave of air-gap flux due to the armature, which links the field winding in the direct axis, and thus constitutes a part of the true armature reaction. The new value of leakage reactance, added to the squirrel-cage reactance, checks observed standstill reactances of synchronous motors; and added to the field reactance checks the values of transient reactance found from oscillographic tests on synchronous generators. With the old reactance formulas, rather arbitrary reductions of the calculated field reactance and tooth tip reactance were necessary before checks with transient and standstill reactances could be secured. Finally, with the old formulas, the calculated increase in "internal voltage" of a synchronous generator under load gave much higher flux densities in low power factor machines than actually do occur, so that arbitrarily reduced values of field leakage under load were used in calculating saturation curves, thus establishing a series of compensating errors.

There is no space to demonstrate the validity of these statements here, and they are simply made to show that the acceptance of the new values of leakage reactance involves a fundamental revision of the generally adopted design constants of synchronous machines. In writing the paper, an effort has been made to make the new formulas and the new definitions such that the further refinements which the future will bring can be added without again altering our conceptions or the orders of magnitude of the characteristic constants of design.

## Nomenclature

$A$ = Maximum ampere-turns per pole of armature reaction

$d_1, d_2, d_3, w$ = Slot dimensions shown in Fig. 1
$D$ = Gap diameter
$f$ = Frequency
$F$ = No-load air-gap field ampere-turns per pole
$g$ = Air-gap length (radial)
$K_B$ = Belt Leakage constant, given by Fig. 6
$K_p, K_d$ = Pitch and distribution factors of armature winding (less than unity)
$K_S$ = A function of winding pitch given by Fig. 2
$L$ = Gross core length
$M$ = $\frac{2\,f\,L\,q\,Z^2}{10^7\,S}$ for inch units
$p$ = Winding pitch expressed as a decimal
$P$ = Number of poles
$q$ = Number of phases
$s$ = Slots per pole = $S/P$
$S$ = Total number of slots
$V$ = Volts per phase
$X_a$ = Armature reaction reactance
$X_B$ = Belt leakage reactance
$X_d$ = Total, or synchronous, reactance in direct axis
$X_l$ = Total armature leakage reactance
$X_z$ = Zigzag leakage reactance
$Z$ = Series connected conductors per phase
$\alpha$ = Angle of end windings as shown in Fig. 4
$\theta$ = Angular phase difference between currents in upper and lower coil sides in one slot
$\phi$ = Flux per pole in c. g. s. lines

## Appendix A

### EXACT CALCULATION OF DIFFERENTIAL LEAKAGE REACTANCE

Chapman* has shown that the total inductance of a winding due to the air-gap flux can be very conveniently calculated by adding the inductances due to the rectangles of flux produced by successive pairs of symmetrically located slots. With this method the smallest unit of flux is that produced by a uniform m. m. f. acting over one slot pitch, so that the permeance variations due to the slot openings are quite satisfactorily taken into account by merely using the average permeance, as in calculating the magnetizing reactance. Thus, the point of view leads to the immediate conclusion that all the harmonic fluxes; (hence the zigzag and belt leakage reactances) are exactly proportional to the fundamental magnetizing reactance. And so the elaborate analyses of the permeance for the zigzag leakage flux as distinct from that for the fundamental flux, that have frequently been employed heretofore, are shown to be unnecessary.

We shall now proceed to calculate the total inductance of a regular, distributed, polyphase winding with $s$ slots and $q$ phase belts per pole ($s/q$ a whole number), and a uniform air-gap length, following Chapman's method. In doing this, the self-inductive voltage produced in the set of coils forming the inner halves of two adjacent phase belts in the same phase by their air-gap flux is considered as the sum of the $s$ voltages produced by the fluxes in the $s$ teeth under one pole. The voltage due to any tooth is proportional to the square of the number of turns linking it, as the reluctance of each tooth pitch is the same, while both the flux per ampere and the volts per unit of flux are proportional to the number of turns. It is most convenient to make all the calculations in relative terms, and, therefore, to take as the unit of inductance the self-inductance which the two adjacent half-phase belts of one phase would have if all their turns were concentrated in one pair of slots exactly one pole pitch apart.

Assuming the winding pitch to be $b$ slots short of full pitch, ($b$ being not greater than $s/q$), and referring to Fig. 8, there will be $\frac{s\,(q-1)}{q} + 1 - b$ central teeth that are linked by all the turns in the two half belts of phase $A$, and hence the total inductance due to these teeth will be:

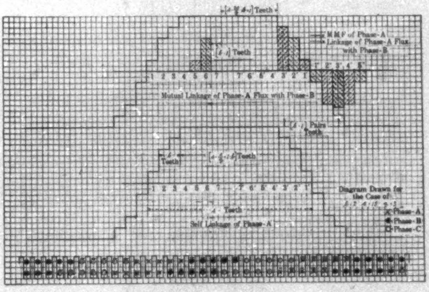

FIG. 8—IDEAL M.M.F. DIAGRAMS FOR POLYPHASE WINDINGS

$$\frac{1}{s}\left(\frac{s\,(q-1)}{q} + 1 - b\right)$$

The next two teeth (3 and 3′) outside these central ones will be linked by $\frac{s-q}{s}$ of the total turns, and will have a permeance $2/s$ of the total permeance, so that they will contribute to the inductance:

$$\frac{2\,(s-q)^2}{s^3}$$

Similarly, consecutive pairs of teeth will each have

---

*Reference No. 13.

$q/s$ less turns than before, until the $b$th pair is reached. The next pair of teeth after that (1 and 1′) will be linked by $\frac{s - 2q - bq}{s}$ of the total turns, so that they will contribute an inductance equal to:

$$\frac{2}{s^3}(s - 2q - bq)^2$$

The following pairs of teeth will have consecutively $2q/s$ less turns than the last, until the outermost pair is reached. Hence, the total self-inductance of Phase $A$ is:

$$L = \frac{1}{s^3}\Bigg[\frac{s^3(q-1)}{q} + s^2(1-b) + 2(s-q)^2 + 2(s-2q)^2$$

$$+ \ldots + 2(s-bq)^2 + 2(s-2q-bq)^2 + 2(s-4q-bq)^2 + \ldots\Bigg]$$

As the sum of the squares of the first $n$ integers is $\frac{n(n+1)(2n+1)}{6}$, this may be reduced to:

$$\frac{1}{6s^3}\Bigg[6s^2\left(s - \frac{s}{q} + 1 - b\right)$$

$$+ 2q^3\left(\frac{s-1}{q}\right)\left(\frac{s}{q}\right)\left(\frac{2s}{q} - 1\right)$$

$$- 2q^2\left(\frac{s}{q} - b - 1\right)\left(\frac{s}{q} - b\right)\left(\frac{2s}{q} - 2b - 1\right)$$

$$+ 2q^2\left(\frac{s}{q} - 2 - b\right)\left(\frac{s}{q} - 1 - b\right)\left(\frac{s}{q} - b\right)\Bigg]$$

and this reduces to:

$$L_{AA} = 1 - \frac{2}{3q} + \frac{q}{3s^3}(2s - 3b^2s - bq + b^3q),$$

$$0 \leqq b \leqq \frac{s}{q}, \qquad \textbf{(1a)}$$

all for a winding pitch not less than $\frac{q-1}{q}$.

The linkages produced by phase $A$ with phase $B$ are similarly found, except that, as the currents in the two phases are out of time phase by $\pi/q$ degrees, and as conditions of symmetry make the out-of-phase components of the linkages cancel with the corresponding components due to the other phases, the effective current in phase $A$ must be reduced by a factor $\cos \pi/q$.

The number of teeth that are linked by all of phase $B$ as well as by all of phase $A$ is $\left(s - \frac{2s}{q} - b + 1\right)$, and these will create linkages with $B$ equal to:

$$\left(\frac{1}{s}\right)\cos\frac{\pi}{q}\left(s - \frac{2s}{q} - b + 1\right)$$

Of the remaining teeth there are $b - 1$ that carry full flux, but are linked by successively fewer coils of the $B$ phase. These contribute an inductance equal to:

$$\frac{1}{s^2}\cos\frac{\pi}{q}\,[(s-q) + (s-2q)$$

$$+ \ldots + (s - (b-1)q)]$$

There are also $b - 1$ pairs of teeth, (3′ and 3″) one of each pair of which carries positive flux and the other an equal negative flux, the former of which is linked by all, and the latter by successively less of the coils of phase $B$. Each pair is linked by successively less of the coils of phase $A$. Hence, these teeth contribute an inductance to phase $B$ of:

$$\frac{1}{s^3}\cos\frac{\pi}{q}\,[q(s - (b-1)q) + 2q(s - (b-2)q)$$

$$+ \ldots + (b-1)q(s-q)]$$

The remaining teeth consists of pairs (6, 5″–7, 4″–1′, 1″–2′, 2″) carrying equal and opposite fluxes and linking the same numbers of coils of phase $B$, so that they contribute nothing to the inductance of phase $B$. Hence, the total increase of inductance of phase $B$ due to phase $A$ is:

$$\frac{1}{s^3}\cos\pi/q\Bigg[s^2\left(s - \frac{2s}{q} - b + 1\right)$$

$$+ s(s - q + s - 2q + \ldots + s - (b-1)q)$$

$$+ q(s - (b-1)q) + 2q(s - (b-2)q)$$

$$+ \ldots + (b-1)q(s-q)\Bigg]$$

which reduces to:

$$L_{AB} = \cos\pi/q\left[\frac{q-2}{q} - \frac{bq^2}{6s^3}(b^2 - 1)\right]$$

$$0 \leqq b \leqq s/q \qquad \textbf{(2a)}$$

The bracketed expression in (**2a**) is to be regarded as zero if it is negative, since the inductance is always positive.

The corresponding expressions for values of $b$ between $s/q$ and $2s/q$, corresponding to winding pitches between one and two phase belts short of full pitch, are, if $q$ is greater than 2:

$$L_{AA} = 1 - \frac{1}{3q} - \frac{1}{s^2}(bs - q/3),\ s/q \leqq b\ \pi\frac{2s}{q} \qquad \textbf{(3a)}$$

and

$$L_{AB} = \cos\pi/q\Bigg[\frac{1}{2q} + \frac{q}{2\ s^2} + \frac{3b}{2s}$$

$$- \frac{3b^2q}{2s^2} + \frac{b^3q^2}{3s^3}\ \frac{bq^2}{3s^3}\Bigg] \qquad \textbf{(4a)}$$

$$s/q \leqq b \leqq \frac{2s}{q}$$

And, the value of the self-inductance of one phase for winding pitches greater than zero by not more than one-phase belt width is:

$$L_{A_A} = \frac{q\,(s-b)}{3\,s^3}\Big[q + (s-b)\,(3\,s - q\,s + b\,q)\Big],$$

$$s - \frac{s}{q} \leqq b \leqq s \tag{5a}$$

There is no need of considering values of $q$ greater than 3, except for full pitch windings, as three-phase belts per pole are all that are used in practise. A squirrel-cage winding always has one slot per pole per phase, so that its differential leakage ratio is the same for all values of pitch. For this case $s/q = 1$, and (**2a**) reduces to:

$$L_{A_B} = \frac{s-2}{s}\cos\pi/s \tag{6a}$$

and the corresponding expression for the $n$th phase is:

$$L_{A_N} = \frac{s - 2\,(n-1)}{s}\cos\frac{(n-1)\,\pi}{s} \tag{7a}$$

The total inductances per phase are obtained by adding the self and effective mutual inductances, as given by the foregoing expressions. For $q = 2$, (**2a**) is zero, so that the total inductance of a two-phase winding is from (**1a**):

$$L_{90^\circ} = 2/3 + \frac{1}{3\,s^3}\,(4\,s - 6\,b^2 s - 4\,b + 4\,b^3) \tag{8a}$$

For $q = 2$, (**1a**) and (**5a**) are identical, so that the single equation (**8a**) is valid over the entire range of pitches from 0 to 1, for two-phase windings.

For a three-phase winding, $q = 3$, and the total inductance of one phase is given by the sum of (**1a**) and twice (**2a**) for pitches between 2/3 and 1, and by the sum of (**3a**) and twice (**4a**) for pitches between 1/3 and 2/3:

$$L_{60^\circ} = 10/9 + \frac{1}{2\,s^3}\,(4\,s - 6\,b^2\,s - 3\,b + 3\,b^3),$$

$$0 \leqq b \leqq s/3 \tag{9a}$$

and

$$L_{60^\circ} = 19/18 + \frac{1}{2\,s^3}\,(5\,s + b\,s^2 - 6\,b - 9\,b^2\,s + 6\,b^3),$$

$$s/3 \leqq b \leqq \frac{2\,s}{3} \tag{10a}$$

(**9a**) and (**10a**) become identical if $b = s/3$.

For a squirrel-cage winding, the total inductance of one phase is, from (**1a**) and (**7a**), placing $b = 0$ and $q = s$ in the former:

$$L_k = 1 + \frac{s-2}{s}\cos\pi/s + \frac{s-4}{s}\cos\frac{2\,\pi}{s} + \dots$$

$$= 1 - \frac{2}{s}\cos\Big(\pi/s + 2\cos\frac{2\,\pi}{s} + 3\cos\frac{3\,\pi}{s}$$

$$+ \dots + (s-1)\cos\frac{(s-1)\,\pi}{s}\Big)$$

$$= \frac{1}{s}\,c\,s\,c^2\,\pi/2\,s \tag{11a}$$

It is interesting to compare the total reactances of the several types of windings by means of these formulas. For a regular three-phase winding, equations (**9a**) and (**10a**) show that:

$$L_{60^\circ} = \frac{10}{9} + \frac{2}{s^2} \text{ for full pitch}$$

$$= \frac{149}{144} + \frac{7}{4\,s^2} \text{ for 5/6 pitch}$$

$$= \frac{5}{6} + \frac{3}{2\,s^2} \text{ for 2/3 pitch}$$

$$= \frac{5}{9} + \frac{1}{s^2} \text{ for 1/2 pitch}$$

$$= \frac{5}{18} + \frac{1}{2\,s^2} \text{ for 1/3 pitch}$$

For a regular two-phase winding (**8a**) shows that:

$$L_{90^\circ} = \frac{2}{3} + \frac{4}{3\,s^2} \text{ for full pitch}$$

$$= \frac{9}{16} + \frac{1}{s^2} \text{ for 3/4 pitch}$$

$$= \frac{1}{3} + \frac{2}{3\,s^2} \text{ for 1/2 pitch}$$

$$= \frac{5}{48} + \frac{1}{3\,s^2} \text{ for 1/4 pitch}$$

For a single-phase winding made by using two legs of a regular three-phase winding, the total inductance is found by substituting 1 for $\cos\pi/2$ in (**2a**) and adding (**1a**) to it, which gives identically the same equation (**9a**) as for the original three-phase winding. Thus, the per cent line-to-line reactance of a three-phase winding is always identical with the per cent three-phase reactance. For a single-phase winding consisting of one leg of a three-phase winding only, the total inductance is given by (**1a**), (**3a**), and (**5a**), whence:

Line to neutral

$$L_{60^\circ} = \frac{7}{9} + \frac{2}{s^2} \text{ for full pitch}$$

$$= \frac{17}{24} + \frac{3}{2\,s^2} \text{ for 5/6 pitch}$$

$$= \frac{5}{9} + \frac{1}{s^2} \text{ for } 2/3 \text{ pirch}$$

$$= \frac{7}{18} + \frac{1}{s^2} \text{ for } 1/2 \text{ pitch}$$

$$= \frac{2}{9} + \frac{1}{s^2} \text{ for } 1/3 \text{ pitch}$$

$$= \frac{5}{72} + \frac{1}{2\,s^2} \text{ for } 1/6 \text{ pitch}$$

Thus, the line-to-neutral air-gap flux reactance of a three-phase winding operated single-phase is 7/10 of its value in three-phase operation for full and half-pitch windings, but is only 2/3 of its three-phase value for 2/3 pitch windings. For a 1/3 pitch winding, it is 4/5 of its three-phase value. These variations are due to the triple harmonic fields that are produced by each phase winding separately, but that are canceled out by a 2/3 pitch, or by a three-phase connection.

Since the zero phase sequence reactance is equal to three times the line-to-neutral, less twice the balanced three-phase reactance, of a three-phase winding, the foregoing expressions lead to the following expressions for the zero phase sequence inductance:

Zero phase

$$L_{60°} = \frac{1}{9} + \frac{1}{s^3}\,(2\,s - 3\,b^2\,s - 6\,b + 6\,b^3),$$

$$0 \leqq b \leqq s/q \qquad (\mathbf{12a})$$

$$= \frac{5}{9} - \frac{1}{s^3}\,(2\,s + 4\,b\,s^2 - 6\,b - 9\,b^2\,s + 6\,b^3)$$

$$\frac{s}{q} \leqq b \leqq \frac{2\,s}{q} \qquad (\mathbf{13a})$$

Hence:

$$\text{Zero phase } L_{60°} = \frac{1}{9} + \frac{2}{s^2} \text{ for full pitch}$$

$$= \frac{1}{18} + \frac{1}{s^2} \text{ for } 5/6 \text{ pitch}$$

$$= 0 \qquad \text{for } 2/3 \text{ pitch}$$

$$= \frac{1}{18} + \frac{1}{s^2} \text{ for } 1/2 \text{ pitch}$$

$$= \frac{1}{9} + \frac{2}{s^2} \text{ for } 1/3 \text{ pitch}$$

All of this zero phase inductance is leakage flux, since the fundamental m. m. fs. of the three-phases cancel with this connection.

The useful, or fundamental, flux produced by the same windings can be readily calculated from the usual pitch and distribution factors, and the difference remaining after the useful is subtracted from the total reactance will give the desired values of total differential leakage reactance.

The ratio of the useful to the total flux generated by a single full-pitch coil is $8/\pi^2$, as this is the ratio of the area of a sine wave to the area of a rectangle whose fundamental it is. This factor, multiplied by the squares of the pitch and distribution constants of the winding, and by the ratio, $q/2$, of the total revolving field produced by all the phases acting conjointly to the field made by a single phase, gives an expression for the reactance due to the useful flux. Or:

$$L_m = \frac{4\,q^3}{\pi^2}\;\frac{\sin^2 \pi/2\,q\,\sin^2 \pi/2\,(1 - b/s)}{s^2 \sin^2 \pi/2\,s} \qquad (\mathbf{14a})$$

Putting $q = 2$ in (**14a**), dividing it into (**8a**), and subtracting unity from the result, we have for the total differential leakage reactance of a two-phase winding, expressed as a ratio to the fundamental magnetizing reactance:

$$\frac{X_{D_{90°}}}{X_m} = \frac{\pi^2\,(s - b)\,(s^2 + b\,s - 2\,b^2 + 2)\,\sin^2 \pi/2\,s}{24\,s\,\sin^2 \pi/2\,(1 - b/s)} - 1 \qquad (\mathbf{15a})$$

If $s$ is large, and $b$ is zero, corresponding to the case of a full-pitch two-phase winding, (**15a**) gives:

$$\frac{X_{D_{90°}}}{X_m}\;\frac{\pi^2\,(s^2 + 2)}{24}\,\sin^2 \pi/2\,s - 1 = \frac{\pi^4}{96}$$

$$+ \frac{\pi^4}{48\,s^2}\left(.412 - \frac{.687}{s^2} + \ldots\right) - 1 \qquad (\mathbf{16a})$$

If $s$ is very large, (**16a**) reduces exactly to (**31**), thus confirming the latter result. For small values of $s$, equation (**15a**) is the only convenient means of obtaining exact values for $X_{D_{60}}$. Numerical values of it for some usual windings are given in Table X.

TABLE X

DIFFERENTIAL LEAKAGE REACTANCE OF TWO-PHASE WINDING EQUATION (15a)

| Pitch deficiency $b$ | $s/2$ = slots per pole per phase | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 0 | 0 2337 | 0.0840 | 0.0468 | 0.0330 | 0.0264 | 0 0229 |
| 1 | 0.2337 | 0.0583 | 0.0334 | 0.0251 | 0.0213 | 0.0193 |
| 2 | | 0.0840 | 0.0285 | 0.0177 | 0.0147 | 0.0138 |
| 3 | | 0.0840 | 0.0468 | 0.0189 | 0.0116 | 0.0096 |
| 4 | | | 0.1019 | 0.0330 | 0.0148 | 0.0080 |
| 5 | | | 0.2337 | 0.0649 | 0.0265 | 0.0130 |
| 6 | | | | 0.1222 | 0.0486 | 0.0229 |
| 7 | | | | 0.2337 | 0.0839 | 0.0398 |
| 8 | | | | | 0.1382 | 0.0650 |

Putting $q = 3$ in (**15a**), dividing it into (**10a**) and (**11a**), and subtracting unity from the result, the total differential leakage reactance for a three-phase, 60 deg. phase belt winding is:

$$\frac{X_{D_{60}}}{X_m}$$

$$= \frac{\pi^2(20\,s^3 + 36\,s - 54\,b^2 s - 27\,b + 27\,b^3 \sin^2 \pi/2\,s}{486\,s \sin^2 \pi/2\,(1 - b/s)} - 1,$$

$$0 \leqq b \leqq \frac{s}{3} \qquad \textbf{(17a)}$$

and

$$\frac{X_{D_{60}}}{X_m}$$

$$= \frac{\pi^2(19\,s^3 + 45\,s + 9\,b\,s^2 - 54\,b - 81\,b^2 s + 54\,b^3) \sin^2 \pi 2\,s}{486\,s \sin^2 \pi/2\,(1 - b/s)} - 1,$$

$$s/3 \leqq b \leqq \frac{2\,s}{3} \qquad \textbf{(18a)}$$

For a full-pitch three-phase winding with a large number of slots per pole, (**17a**) may be reduced to:

$$\frac{X_{D_{60}}}{X_m} = \frac{2\,\pi^2\,(5\,s + 9)}{243} \sin^2 \pi/2\,s - 1$$

$$= \frac{5\ \pi^4}{486} + \frac{\pi^4}{54\,s^2}\left(0.543 - \frac{0.672}{s^2} + \ldots\right) - 1 \quad \textbf{(19a)}$$

If $s$ is very large, (**19a**) reduces exactly to (**32**).

Numerical values of (**17a**) and (**18a**) for some usual three-phase windings are given in Table XI.

For a squirrel-cage winding, $q = s$ and $b = 0$, so that by substituting these values in (**15a**) and dividing the result into (**14a**), the differential leakage reactance is found to be:

TABLE XI
DIFFERENTIAL LEAKAGE REACTANCE OF THREE-PHASE WINDINGS
EQUATIONS (17a) AND (18a)

| Pitch deficiency $b$ | $s/3$ = slots per pole per phase | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 0 | 0.0966 | 0.0284 | 0.0140 | 0.0089 | 0.0064 | 0.0052 |
| 1 | 0.0966 | 0.0235 | 0.0115 | 0.0074 | 0.0055 | 0.0045 |
| 2 | 0.0966 | 0.0284 | 0.0111 | 0.0063 | 0.0044 | 0.0035 |
| 3 | | 0.0284 | 0.0140 | 0.0069 | 0.0041 | 0.0030 |
| 4 | | 0.0284 | 0.0143 | 0.0089 | 0.0050 | 0.0031 |
| 5 | | | 0.0137 | 0.0092 | 0.0064 | 0.0040 |
| 6 | | | 0.0140 | 0.0089 | 0.0068 | 0.0052 |
| 7 | | | | 0.0083 | 0.0067 | 0.0056 |
| 8 | | | | 0.0089 | 0.0062 | 0.0055 |
| 9 | | | | | 0.0057 | 0.0052 |

$$\frac{X_{D_K}}{X_m} = \frac{\pi^2}{4\,s^2}\,c\,s\,c^2\,\pi/2\,s - 1 \qquad \textbf{(20a)}$$

If $s$ is large, this may be developed into a series of which only the first term need be considered:

$$\frac{X_{D_K}}{X_m} = \frac{\pi^2}{12\,s^2}\left(1 + \frac{\pi^2}{20\,s^2} + \frac{\pi^4}{504\ \ s^4} + \ldots\right) \qquad \textbf{(21a)}$$

For large values of $s$, (**21a**) agrees exactly with (**25**), thus confirming the previously derived formula for zigzag leakage reactance.

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## Discussion

**B. A. Behrend:** In connection with Mr. Alger's very complete investigation of the factors which determine the armature reactance of a synchronous machine the question may be raised whether it is more satisfactory for the designer to derive his characteristic data from comparison with known similar designs or by a fresh calculation for each particular case. As a rule the designs vary comparatively little, thus making it possible to obtain design data by comparison. The analysis of the constituent parts of the total leakage field as carried out by Mr. Alger is in keeping with the desire to leave no part of the theory unexplored and to link together the leakage of synchronous and induction machines. In this very painstaking and intricate procedure I doubt that a method which is evolved by one designer and which suits his method of working is likely to appeal equally to another designer. I am inclined to view such methods as to a great extent individual though notwithstanding this they are of the greatest importance in clarifying obscure problems and showing us the empirical basis of our assumptions. It would be interesting to know just how many factors could be grouped together without entailing errors greater than those ordinarily encountered in the limitations of design and workmanship.

**A. A. Bennett:** I wish to call attention to Fig. 4. The currents flowing along the bent end windings there are supposed to be distributed in sinusoidal fashion, and they are then analyzed into two components, one flowing peripherally and the other axially.

I object to the idea here expressed of analyzing something into components which have no meaning. We cannot analyze the cosine function into the product of a co function by a sine function. The peripheral current is supposed to be flowing along a conductor, but it isn't a real current in any proper sense. At one point, the current is large and flowing in one direction; at another point, there is no current at all, and, at still another point, it is large and flowing in the opposite direction.

**E. B. Shand:** Mr. Alger has modified somewhat the methods of separating out the machine fluxes so that the resultant leakage reactance is considerably less than that given by a number of other formulas. I have always considered that these latter formulas, beginning with the classic one of Dr. Arnold, were inconsistent in using fluxes which should properly be classed as cross-magnetizing and thereby gave results which could not be entirely reconciled with all data found on tests. This was pointed out in my discussion on "*Variable Armature Leakage Reactance in Salient-Pole Synchronous Machines*" by V. Karapetoff, A. I. E. E. TRANS., 1926, p. 733. Formulas of the type of this present may be relied upon to give more complete information of machines.

**P. L. Alger:** Mr. Shand's remark agrees with what many of us have felt for a long time, that the necessity for using a lower value of leakage reactance to check transient performance than for synchronous operation indicated that the old value of synchronous leakage reactance was too high. The new and lower values of leakage reactance will, I am sure, clear up many discrepancies heretofore existing in synchronous-machine theory. It is well to remember, however, that the point of division between the reactances of armature reaction and armature leakage cannot be very exactly defined. For example, my colleague, D. H. Harms, has pointed out that a small part of the fundamental flux wave in the direct axis, due to the armature reaction, passes along the air gap space without entering the field at all, and that this part is truly a leakage reactance, although in the paper it is included with the armature reaction. From Appendix B of reference 3, the magnitude of this part of the reactance is approximately:—

$$\Delta X_{ad} = \frac{P^2 g^2}{3 D^2} X_{ad},$$

which usually amounts to less than 0.5 per cent of $X_{ad}$, but may be as much as 2 per cent in some high-speed machines. This more exact distinction between the two elements of the reactance makes the calculated values of transient reactance a trifle higher.

I agree with Professor Bennett that my conception of the axial end leakage flux, as due to a discontinuous peripheral current, is a highly artificial one, and that it would be more satisfying to consider the end leakage flux as a whole. I can only say that the device adopted affords a short cut that leads to simpler and more definite results than I could find by any other method.

# The Reactances of Synchronous Machines

BY R. H. PARK[1] and B. L. ROBERTSON[1]
Associate, A. I. E. E. Associate, A. I. E. E.

***Synopsis.**—Until somewhat recently, synchronous machine theory has been satisfied with a relatively few characteristic constants, or reactances, in terms of which the behavior of machines has been calculated. Present theory, however, requires many more coefficients. There are now generally recognized two values each of leakage, synchronous, and transient reactance which correspond to the two symmetrical axes of magnetization of the armature current and which refer to balanced operation. Negative and zero phase-sequence reactances are also employed to determine operation under unbalanced conditions, and it is possible and desirable to distinguish other reactances. In view of the increasing complexity of the subject it is felt that a critical survey of it is in order and the object of the paper has been to provide that survey.*

*The paper has been divided into two parts. Part I is descriptive, and treats the subject with regard to those factors which are important to application or operating engineers, and to designers. In particular, the major types of reactances which include the synchronous, transient, and phase-sequence reactances, are discussed. These quantities are defined and their methods of test outlined. It appears necessary to consider a second type of transient reactance, namely sub-transient reactance. Both reactances may be determined from short-circuit oscillograms as illustrated in the paper. A table is included which gives the numerical range of reactances for the various types of synchronous machines.*

*Part II discusses the theoretical considerations, with a view to broadening and classifying existing conceptions of reactance. It includes the effect of external reactance on negative phase-sequence reactance, and the variation in this latter quantity depending upon whether current or voltage is impressed on the machine. An important aspect of the division of synchronous reactance into armature reaction and leakage reactance is discussed. Transient reactance is shown to be the difference between synchronous reactance and the ratio of the mutual reactance between armature and field and the total field reactance. Calculations are included to show that the short-circuit and open-circuit time-constants are related to each other in a simple manner.*

*The appendixes cover the following subjects:*

*a. Application of the Principle of Superposition to Synchronous Machine Analysis.*
*b. Replacing the Effect of Induced Field Currents by Employing Transient instead of Synchronous Reactances.*
*c. Significant Rotor Circuits in Addition to the Main Field Winding (which affect transient reactances).*
*d. The Negative Phase-Sequence Reactance of a Synchronous Machine with Negative Phase-Sequence Voltage Impressed.*
*e. Construction of Equivalent Circuits: Concept of Field Leakage Reactance.*
*f. Calculation of Total Field Reactance.*
*g. Relation of the Mutual Reactance Between Armature and Field to the No-Load Excitation Current.*
*h. Relation Between Three-Phase and Single-Phase Reactances.*
*i. Discussion of the System of Notation Used in the Paper.*
*j. Per-Unit Representation of Quantitities.*

* * * * *

## THE REACTANCES OF SYNCHRONOUS MACHINES

IN the course of the development of the theory of synchronous machines there has come into use along with an increased knowledge of the behavior of such machines under varying conditions of operation, a correspondingly increased number of characteristic constants or coefficients referring generally to reactive voltages, in terms of which this behavior is calculated.

Thus, in place of the concept which was formerly held of a single leakage reactance and armature reaction, there are at present generally recognized two values each of leakage, synchronous, and transient reactances, corresponding to the two symmetrical axes of magnetization of armature current. In addition to these reactances, which refer to balanced operation, there are also values of negative and zero phase-sequence reactance, which are employed to determine operation under unbalanced conditions. It is also possible and desirable to distinguish other reactances, particularly those which obtain with the rotor stationary, and those which are encountered by harmonic currents. At the same time, improvements have recently been made in methods of calculating leakage reactance and armature reaction. Therefore, on account of the increasing complexity of the subject it is felt that a critical survey of it is in order. The object of the paper has been to provide a survey of this character which would be of value both from the standpoint of system analysis and from that of fundamental theory.

Since the requirements of these two points of view are to a considerable extent distinct, the paper has been divided into two parts. Part I treats the subject with regard to those factors which are important to designing and application engineers, and to operating engineers. Part II discusses in detail the theoretical considerations involved, with a view to broadening and classifying existing conceptions of reactance.

## PART I. REACTANCES PARTICULARLY AFFECTING OPERATION

In the analysis of system stability, and in the calculation of the effect of short-circuits, the factors of interest to operating engineers are those which relate to the behavior of the machine as viewed from the armature terminals. The most significant of these factors are the armature reactances of machines to normal frequency current having any distribution between phases, any power-factor, and whether transient or sustained; also, in connection with transient components of current, their rates of decay, or decrements.

*Types of Reactances.* The major types of armature reactances then are to be distinguished according to:

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A. Distribution; that is, the relative distribution of current between phases.

Any distribution of armature current may be expressed as the superposed sum of three symmetrical components:[3]

a. Balanced three-phase currents of normal phase rotation, or *positive phase-sequence*,

b. Balanced three-phase currents of reverse phase rotation, or *negative phase-sequence*, and

c. Balanced three-phase currents of equal time phase, or *zero phase-sequence*.

B. Method of application in time of positive phase-sequence currents.

Here it is desirable to distinguish between:

a. Steadily applied, or sustained currents,

b. Suddenly applied, or transient currents.

In the case of armature reactances these differences are due to the transient currents induced in the rotor circuits when armature current is suddenly applied. If, as is generally so, there are closed circuits on the rotor in addition to the field winding, as for example an amortisseur, it is found that some of the currents in the rotor circuits may die away very rapidly. In order to distinguish between the effect of these currents and the effect of those which die away slowly, it is desirable to establish two (or more) transient reactances. The higher reactance, *i. e.*, the reactance which depends on currents that die away slowly, is then referred to as the *transient reactance* of the machine. The lower reactance may be referred to as the *sub-transient reactance* on account of its lower value.

C. Position of the rotor with respect to axis of magnetization of positive phase-sequence currents.

When the rotor is moving synchronously, the positive phase-sequence current can be resolved into two components, one of which magnetizes in the axis of the poles, and the other in the inter-polar space. Accordingly, these components are referred to as *direct* and *quadrature*,[4] and the corresponding reactances are:

a. Direct, or

b. Quadrature.

Thus, to summarize, the types of armature reactance which have been considered so far are to be distinguished according to whether they are:

A. Positive, negative, or zero phase-sequence,

B. Sustained, transient, or sub-transient,

C. Direct or quadrature.

The determination of a suitable notation for these reactances should depend more upon present and future requirements than merely upon previous practise.

After careful consideration of the subject, it seemed that a consistent notation could be obtained by denoting the various types of reactance according to the method outlined below:

A. Distribution.
  Armature reactances
    Positive phase-sequence $x_1$, or no subscript
    Negative phase-sequence $x_2$
    Zero phase-sequence $x_0$
B. Application in time.
  Sustained—No special indication.
  Transient—One prime, *i. e.*, $x'$
  Sub-Transient—Two primes, *i. e*, $x''$

If it is desired to distinguish other degrees of transiency, additional primes may be added.

C. Position of rotor.
  Direct $x_d$
  Quadrature $x_q$.

The various armature reactances of the types discussed are then represented by the notation shown in Table I.

TABLE I

ARMATURE REACTANCES

| | |
|---|---|
| $x_d$ | Direct synchronous, positive phase-sequence. |
| $x_q$ | Quadrature synchronous, positive phase-sequence. |
| $x_d'$ | Direct transient, positive phase-sequence. |
| $x_q'$ | Quadrature transient, positive phase-sequence. |
| $x_d''$ | Direct sub-transient, positive phase-sequence. |
| $x_q''$ | Quadrature sub-transient, positive phase-sequence. |
| $x_2$ | Negative phase-sequence. |
| $x_0$ | Zero phase-sequence. |

*Definitions and Methods of Test.* Synchronous reactance: The problem of determining the relations between fundamental components of armature voltage and current during steady operation has been thoroughly analyzed by Blondel,[5] Arnold,[6] and Doherty and Nickle.[7] The accepted theory may be briefly summarized as follows:

First, the balanced three-phase system of armature currents is resolved into two component three-phase systems: one in which the current in each individual phase reaches a maximum at the instant that the axis of the field pole coincides with the axis of magnetization of the phase under consideration; and another in which the current in each individual phase reaches maximum at the instant the axis of magnetization is in line with the axis midway between poles, that is, one-quarter cycle later. The former is called the *direct* component because it produces direct component of armature reaction. The latter is the *quadrature* component.

Then coefficients are defined expressing the ratio of reactive component of voltage to armature current for each type of current. These coefficients are the *direct* and *quadrature* synchronous reactances of the machine.

These reactances may be expressed either in ohms, or as a ratio of their reactance in ohms to normal ohms, where normal ohms is the ratio of normal voltage and current. When so expressed, they are referred to as *per-unit reactances.*[8] Thus:

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[3] Reference (11).

[4] A considerably broader conception of direct and quadrature quantities is developed in Part II.

[5] Reference (13).

[6] Reference (12).

[7] Reference (8).

$$\text{Per-unit reactance} = \frac{\text{reactance in ohms}}{\text{normal ohms}}$$

$$\text{Normal ohms} = \frac{\text{normal line-to-neutral voltage}}{\text{normal line current}}$$

Consequently, *per-unit direct synchronous reactance* is defined as the *per-unit* fundamental component of reactive armature linkages, due to unit sustained direct component of armature current. Quadrature synchronous reactance is defined similarly. The resultant terminal voltage is then found by subtracting the reactance drop in each axis from the no-load terminal voltage corresponding to the existing field current, assuming no saturation. Hence, if the machine is dead short-circuited at normal voltage, the reciprocal of the per-unit sustained armature current is equal to the per-unit direct synchronous reactance.

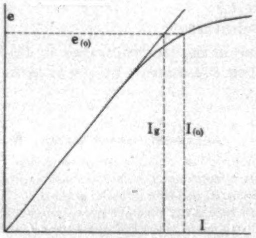

FIG. 1—SATURATION CURVE

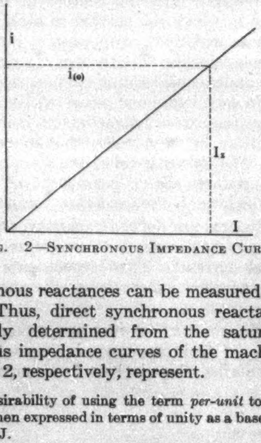

FIG. 2—SYNCHRONOUS IMPEDANCE CURVE

Synchronous reactances can be measured accurately by test. Thus, direct synchronous reactance, $x_d$, is conveniently determined from the saturation and synchronous impedance curves of the machine, which Figs. 1 and 2, respectively, represent.

In the figures:

$e_{(0)}$ = normal armature voltage.[9]

$i_{(0)}$ = normal armature current.

$I_{(0)}$ = field current required to produce $e_{(0)}$ at no-load.

$I_g$ = field current required to force normal flux across the air-gap.

$I_s$ = field current required to produce normal armature current at short-circuit.

Synchronous reactance, in accordance with established practise, is understood to be calculated on the basis of no saturation, and all quantities are referred to the air-gap line. Hence, the direct component of synchronous reactance is measured as the ratio of $I_s$ and $I_g$, *i. e.*,

$$x_d = \frac{I_s}{I_g}$$

The quadrature synchronous reactance, $x_q$, of a three-phase machine may be determined by the following method.[10] The machine, coupled in electrical quadrature to a relatively very large synchronous motor and connected to the motor lines, is operated unexcited. The ratio of the armature voltage, *e*, to the corresponding armature current, *i*, is the quadrature synchronous reactance in ohms. Expressed as a per-unit quantity, it is:

$$x_q = \frac{e}{i} \cdot \frac{i_{(0)}}{e_{(0)}} .$$

FIG. 3—"SLIP METHOD" OF OBTAINING $x_d$ AND $x_q$

The disadvantage of this scheme is the limitation it imposes on the sizes of the machines which may be tested, due to the fact that the driving motor must be of sufficient size so that its angular displacement will not be appreciable.

A method, referred to as the "slip method," affords, however, a practical means of obtaining $x_q$, and may also be used to obtain $x_d$. The machine to be tested is left unexcited and a three-phase voltage is applied to its armature. The rotor is coupled to a driving motor, of sufficient capacity to overcome the reluctance torque at the reduced voltage, and is run at a low value of slip. In this manner the poles are slipped past the m. m. f. wave. The magnetizing current is then a function of the rotor position with respect to the m. m. f.

The oscillogram of Fig. 3 is the result of such a test.

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[8] The desirability of using the term *per-unit* to characterize reactance, when expressed in terms of unity as a base, is discussed in Appendix J.

[9] The subscript, (0), enclosed in parentheses, refers to normal values, and should not be confused with the subscript, 0, used to indicate zero phase-sequence quantities.

[10] Two alternative methods of obtaining $x_q$ are given in References (3) and (7) respectively.

It will be noticed that both the current and voltage are modulated harmonically as the pole position changes, the variation in voltage being due to reactance drop in the source of power employed.

When the poles line up with the axes of the phases, position (a) on the above curve, the current is a minimum. At this position the ratio of voltage to current is the direct synchronous reactance. Similarly, when the axes of the phases are midway between the poles, position (b), the ratio of voltage to current is the quadrature synchronous reactance.

This last means of testing for the synchronous reactances is simple and has several points of advantage. Thus, the power supply to the tested machine can be small, just enough so that the meter readings are easily obtained. Corresponding readings, or oscillograms, of voltage and current can be taken, and the calculated reactances plotted as a function of time or pole position. Also, the driving motor need only be of sufficient capacity to supply the reluctance torque. Moreover, if the motor speed is well regulated, so as to produce a low value of slip, there will be no difficulty in taking readings directly from indicating instruments, since the swings of the meter needles can be easily followed. In some cases, it may be desirable to take oscillograms of both voltage and current.

*Transient reactance.* When a machine is subjected to a three-phase short-circuit from an initial condition of no-load, the flux-linkages in every rotor circuit must initially stay constant. But, since the armature current tends to demagnetize these circuits, it is necessary for the currents in them to increase, in order that the condition of constant flux-linkages in each circuit may be fulfilled.

This increase in rotor m. m. f. is responsible for the familiar fact that the initial short-circuit current of a machine is greater than that obtained under sustained conditions, after the induced d-c. currents in the field and additional rotor circuits have died away. The resultant armature current is calculated in terms of the voltage before the short-circuit, as the ratio of that voltage to a value of reactance referred to as the *transient* reactance of the machine.

More specifically, this reactance is, of course, the direct component of transient reactance, since it involves only reactive or direct axis component of current. Thus, direct transient reactance, $x_d'$, is

$$x_d' = \frac{e}{i}$$

where $e$ is the voltage preceding short-circuit and $i$ is the symmetrical component of armature current just after the short-circuit.

The exact interpretation of this definition would imply that the current $i$ is to be measured as the value of the envelope of the wave of symmetrical component of current, as projected to the instant of short circuit. But, in machines with closed rotor circuits in addition to the field, this initial value may not satisfactorily represent the performance of the machine on account of the fact that the current induced in some or all of these additional circuits may die away very rapidly. It is, therefore, desirable to establish the conception of transient reactance proper, as the value of apparent transient reactance which applies to the current variation after the rapidly decaying components of current have died away. It can be obtained, as shown in Fig. 4, by projecting the envelope of the current wave to the instant of short circuit, neglecting the first one or two peaks. Point (b) of Fig. 4 corresponds to the transient reactance proper. The reactance determined by the projected value of the envelope of the first few peaks of the current wave, point (a), is then referred to as the sub-transient reactance. In practise, the low value of this reactance may be due in part to saturation in the leakage paths.

Practically, the value of short-circuit current can be expressed as the sustained value plus one or more components, each of which die away exponentially. Transient reactance proper is then the reciprocal of the current that would exist at $t = 0$ if the high-speed terms were absent. These relations may be made clear by reference to Fig. 5, which shows the observed values of symmetrical component of armature current from a three-phase short-circuit test on a large water wheel generator. The test was taken at reduced voltage so as to exclude saturation, and the per-unit values of current have been multiplied by a factor so as to refer to a test at normal voltage without saturation.

FIG. 4—DETERMINATION OF $x_d'$ AND $x_d''$ BY METHOD OF PROJECTION

The per-unit current is expressible in this case as,

$$i = 1.54 + 1.83\,\epsilon^{-.653t} + 1.06\,\epsilon^{-51t},$$

the term with high decrement factor being due to the presence of a copper short-circuiting collar at the top of the pole. The values of direct transient reactance are then,

$$x_d'' = \text{direct sub-transient} = \frac{1.0}{1.54 + 1.83 + 1.06}$$

$$= 0.226$$

and,

$$x_d' = \text{transient} = \frac{1.0}{1.54 + 1.83} = 0.297$$

So far, transient reactance has been interpreted only in terms of the no-load short-circuit current of the machine. But, clearly, it may also be regarded as the reciprocal of the ratio of suddenly applied balanced current, to the reactive voltage due to this current. It is, therefore, similar to synchronous reactance, except referring to suddenly applied instead of sustained currents. From this standpoint it will of course have both a direct and quadrature value, each of which in turn can be transient or sub-transient. If, however, as is often the case, there is no really effective winding in the quadrature axis of the machine, the transient reactance in this axis should be taken equal to synchronous. Thus, the term *sub-transient reactance* will always refer to the "high-speed" phenomena in either axis. Moreover, if, as in the case of the machine to which the data of Fig. 5 refer, there happens to be no rotor winding in the quadrature axis, the sub-transient quadrature reactance will also equal the synchronous in that axis. Hence, in this case,

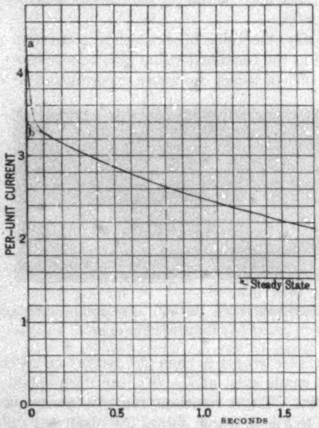

FIG. 5—DECREMENT OF SYMMETRICAL COMPONENT OF CURRENT THREE-PHASE SHORT CIRCUIT ON A 20,000-KV-A. WATERWHEEL GENERATOR

$$x_q'' = x_q' = x_q.$$

On the other hand, for machines equipped with amortisseurs, the value of the sub-transient quadrature reactance will be different from the corresponding synchronous value, although, as before,

$$x_q' = x_q$$

since there is no really effective winding in this axis. In practise, an amortisseur always has a decrement sufficiently high so that its reactance is sub-transient.

Thus, the per-unit sub-transient reactance of a machine, in either the direct or quadrature axis, is defined as the per-unit value of positive phase-sequence voltage, due to the sudden application of a positive phase-sequence current of normal amount; while transient reactance is the corresponding apparent value that obtains after the "high-speed" transients have died out. The four coefficients will, therefore, be

$x_d'$ direct transient reactance
$x_q'$ quadrature transient reactance
$x_d''$ direct sub-transient reactance
$x_q''$ quadrature sub-transient reactance

It has been pointed out that the direct sub-transient reactance can be determined from short-circuit tests. It is also possible to measure it by suddenly opening up a sustained short circuit, that is, applying the equivalent of a negative current equal in magnitude to the sustained current. Also, either direct or quadrature transient reactance can be found by impressing a direct or quadrature voltage, respectively, on the terminals, directly or through a reactance. In all of these cases the ratios of voltage to current, as shown on oscillograms, vary progressively from an initial value equal to sub-transient reactance, through transient, to a final value equal to synchronous reactance.

Another method which is sometimes useful in determining $x_d'$ is to determine oscillographically the time-constant of the decay of armature voltage and current, respectively, with the armature open-circuited and short-circuited. If these time-constants are respectively $T_0$ and $T_0'$, $x_d'$ may be found from the relation[11]

$$\frac{x_d'}{x_d} = \frac{T_0'}{T_0}$$

provided that $x_d$ is already known.

A convenient method, which may be used in testing for both $x_d''$[12] and $x_q''$[13] is to apply a single-phase line-to-line voltage to the machine, the rotor being held still. The field is shorted through an ammeter and the rotor moved until the meter reading is a maximum, at which position the rotor is directly under the center of the phase. The direct sub-transient reactance, in ohms, is one-half[14] the ratio of the armature voltage to the armature current under these conditions.

The pole is moved slowly until the field ammeter reads zero, showing that the pole is in quadrature with the axis of magnetization. Then, the quadrature sub-transient reactance, in ohms, is again one-half[14] the ratio of the armature voltage to the armature current.

For delta-connected machines the line-to-line reactances are similarly divided by two and the equivalent Y-circuit used.

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[11] See Part II.

[12] If there are no auxiliary windings on the rotor this reactance is transient, *i. e.*, $x_d'$. Without such windings the method may also be used to obtain synchronous reactance by leaving the field open-circuited.

[13] If amortisseur windings are not present this reactance is the quadrature synchronous reactance.

[14] See Appendix H.

*Negative phase-sequence reactance.* In the case of a machine rotating synchronously the application of fundamental negative phase-sequence current gives rise to negative phase-sequence fundamental and positive phase-sequence third harmonic voltages from line-to-line and from line-to-neutral. The per-unit negative phase-sequence reactance of a machine is thus equal to the per-unit fundamental phase voltage, or the per-unit line-to-line voltage, due to normal negative phase-sequence current supplied at the machine terminals.

On the other hand, if the rotor is not moving exactly synchronously the line-to-line voltages will not be purely fundamental, but, as is shown in Part II, they will contain slip frequency components. On this account, the direct determination of negative phase-sequence reactance by test is often inconvenient.

However, it can be determined very easily by static test since the negative phase-sequence reactance of a machine is very nearly equal to the average[15] of $x_d''$ and $x_q''$, *i. e.*,

$$x_2 = \frac{x_d'' + x_q''}{2}$$

*Zero phase-sequence reactance.* The application of fundamental zero phase-sequence current to a synchronous machine gives rise to pulsating third harmonic m. m. f. in the air-gap and end-windings, and to a slot flux the magnitude of which varies widely with the winding pitch. Thus, with other than full pitch coils, the slot flux is diminished by the presence, in the slots, of coil sides carrying current in opposite directions. Zero phase-sequence slot reactance is thus very sensitive to pitch, and because of the fact just previously mentioned is a minimum at $^2/_3$ pitch. The zero phase-sequence air-gap leakage also varies accordingly and disappears at $^2/_3$ pitch, since in this case there is no air-gap m. m. f. There is no armature reaction m. m. f. due to zero phase-sequence currents. Hence zero phase-sequence reactance is very small, say, from 15 to 60 per cent of the direct sub-transient reactance. The effect of the motion of the rotor is very small, and, as a consequence, there are no appreciable harmonic voltages. *Per-unit zero phase-sequence reactance* is defined as the per-unit phase voltage with normal zero phase-sequence current applied. While its definition implies a condition under which the rotor is moving at normal speed, the difference in test result, if the rotor is stationary, is inappreciable.

## DECREMENTS

*Symmetrical component of current.* As pointed out in the discussion of transient reactance, the decrement curve of the transient armature current of a machine on short-circuit will, in general, be composed of several simple decrement terms, or exponentials. That is, the current will be expressible as a series

$$= a + b\,\epsilon^{-\frac{t}{T_b}} + c\,\epsilon^{-\frac{t}{T_c}} + \ldots .$$

where $a$ is the sustained component of current, and $b$, $c$, etc., are the transient components of current with time-constants $T_b$, $T_c$, etc., respectively. In practise all but one of these time-constants will be small, *i. e.*, less than about one-twentieth sec., while for dead short-circuits the remaining time-constants will vary in large machines from about 0.5 to 2.5 sec.

Thus, a few cycles after the occurrence of a short, from an initial condition of no-load and voltage $e$, the armature current will be

$$i = e\left[\frac{1}{x_d} + \left(\frac{1}{x_d'} - \frac{1}{x_d}\right)\epsilon^{-\frac{t}{T_0'}}\right]$$

where $T_0'$ is the short-circuit time-constant of the machine.

If the machine is operating at no-load and its field winding is short-circuited, the variation of armature voltage, shortly after the beginning of the transient, will follow a decrement having a time-constant $T_0$, which is larger than the short-circuit time constant $T_0'$. These time-constants are related by the simple expression

$$T_0' = \frac{x_d'}{x_d}\,T_0.$$

As it happens that the open-circuit time-constant of most large machines is about five sec., the above relation provides an easy means of determining $T_0'$ when the other two quantities are known. The time constant $T$ for a short circuit through an external reactance $x$ is then given as

$$T = \frac{x_d' + x}{x_d + x}\,T_0.$$

This also applies to the case of single-phase short circuits. Thus, on single-phase short circuits, the positive phase-sequence component of current is to be calculated as the current that would exist when an equivalent[16] three-phase short circuit is applied.

In the case of short circuits under load the time-constants of the rotor circuits in the quadrature axis are also involved. Except for solid rotor turbo alternators, these are all so fast, however, as not to merit attention from an operating standpoint.

The case of turbo alternators is also complicated to some extent by the large amount of saturation which exists in the rotor leakage paths. The effect of saturation in such paths is not confined to turbo alternators only, but is encountered to some extent in short circuits of salient pole machines. Its effect does not, however, greatly modify the general conclusions stated.

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[15] See Appendix D.

[16] The equivalent reactance of a line-to-line short is the negative phase-sequence reactance viewed from the point of short, while for line-to-neutral shorts it is the sum of the negative and zero phase-sequence reactances. The negative and zero phase-sequence currents can, of course, be found by applying the conditions which hold at any instant,—that for line-to-line faults, the positive and negative components of current are equal in the fault; and that for line-to-neutral faults, all three components are equal in the fault.

*D-c. component.* On dead short circuits, the time-constant of the d-c. component is

$$\tau = \frac{1}{2\,\pi f}\;\frac{x_2}{r}\text{ seconds}$$

while if the machine is short-circuited through an external reactance, $x$, the time-constant is

$$\tau = \frac{1}{2\,\pi f}\;\frac{x_2 + x}{r}\text{ seconds}$$

where $r$ is the armature resistance as a per-unit quantity.

The time-constant on single-phase short-circuit is calculated as for the equivalent three-phase short-circuit.

*Range of magnitude of reactances and time-constants.* It is noticeable that in any certain type of machine the average value of each of the particular reactances appears to be a rather constant quantity, the deviation from which is not very great. Thus it is possible to obtain tables showing the general limits and the average values of the reactances, such as Table II.

The first figures in any group of three quantities indicate the lower limit, the second figures are the average, and the third figures, the upper limit. It is understood that they are not absolute values, but are representative of most machines. Where only two quantities are mentioned, the lower and upper limits are meant. If only one term is given it is the average reactance.

## PART II

### THEORETICAL CONSIDERATIONS

The general problem of calculating the performance of a synchronous machine does not admit of any but the most difficult forms of analysis, unless the effects of saturation and hysteresis are neglected. Therefore, they are not considered in the analysis which follows. Practically, these effects are small in a large number of cases. In those cases where their consideration becomes necessary, the final result, or the coefficients, may be "shaded."

Since saturation and hysteresis are neglected, linear relations exist between current and magnetic flux. It then follows, as is shown in detail in Appendix A, that *for a given motion or position* of the rotor, the currents and voltages in any part of the machine, due to any currents or voltages impressed at its terminals, may be found by superposing the effects that would result from the action of each separately. Thus, there will exist factors of proportionality between the voltage or current impressed at any terminal, and the voltages and currents at all other points of the machine.

For instance, if the armature of the machine is open-circuited, a steady voltage impressed on the field will give rise to a steady direct current in the field, and to fundamental and harmonic voltages at the armature terminals. On the other hand, if, say, one phase of the

TABLE II
TYPICAL VALUES OF REACTANCE

| | $x_d$ | $x_q$ | $x_d'$ | $x_q'$ | $x_d''$ | $x_q''$ | $x_2$ | $x_0$* | $T_0$ (sec.) |
|---|---|---|---|---|---|---|---|---|---|
| Synchronous Motors | | | | | | | | | |
| High-Speed | 0.65–0.80–0.90 | 0.50–0.65–0.70 | 0.15–0.25–0.35 | 0.50–0.65–0.70 | 0.10–0.18–0.25 | 0.12–0.20–0.30 | 0.11–0.19–0.25 | 0.02–0.15 | 2–4 |
| Low-Speed | 0.80–1.1 –1.5 | 0.60–0.80–1.10 | 0.40–0.50–0.70 | 0.60–0.80–1.1 | 0.25–0.35–0.45 | 0.30–0.40–0.50 | 0.25–0.35–0.50 | 0.04–0.27 | |
| Synchronous Condensers | av. 1.60 | av. 1.00 | 0.40–0.50 | av. 1.00 | 0.25–0.30 | 0.25–0.35 | 0.25–0.32 | 0.04–0.10 | 5–7 |
| Waterwheel Generators | 0.60–1.0 –1.25 | 0.40–0.65–0.80 | 0.20–0.35–0.45 | 0.40–0.65–0.80 | 0.15–0.22–0.35 | 0.40–0.65–0.80 | 0.25–0.45–0.60 | 0.02–0.21 | 3–6 |
| Turbo Alternators | | | | | | | | | |
| Solid Rotor | av. 1.15 | av. 1.0 | 0.15–0.25 | 0.15–0.25 | 0.08–0.15 | 0.10–0.20 | 0.08–0.13 | 0.01–0.08 | 4–7 |
| Laminated Rotor | av. 1.15 | av. 1.0 | 0.15–0.25 | av. 1.0 | 0.08–0.12 | 0.20–0.30 | 0.11–0.21 | 0.01–0.08 | |

*$x_0$ varies from about 15 per cent to 60 per cent of $x_d''$, depending upon winding pitch.

armature is short-circuited, a steady voltage applied to the field will give rise to steady and harmonic currents in the field, and harmonic currents and voltages, respectively, in the shorted and open armature phases. The ratios of these various currents or various voltages to the impressed field voltage may be referred to as the characteristic coefficients of the machine with reference to the particular condition of operation and the particular terminal quantity impressed, which in the illustrative case under consideration happens to be field voltage.

In general, characteristic coefficients can be established to cover any combination of impressed and resultant quantities, of any frequency, in any of the four distinct terminal circuits[17] of the machine comprising the three armature phases and the field winding. These coefficients may be further distinguished from each other according to the rate and time-phase of application of the impressed quantities, the character of the terminal circuits on which these quantities may be impressed, the motion and position of the rotor, and the time-phase of the resultant quantities relative to the impressed quantities.

The general problem of classifying and establishing a nomenclature for all of the various types of coefficients would be difficult, especially as there is no generally accepted name for the voltage, due to a voltage, or the current due to a current.[18] Moreover, the necessity for a careful study of the broad subject is not pressing at present, although it is anticipated that as progress is made in the analysis of machine performance, the recognition and employment of an increasing number of characteristic coefficients will take place.

However, the specific problem of classifying and studying that particular class of coefficients, which refers to the reactive voltages and currents in synchronous machines, is relatively straightforward: at the same time it is important, in view of the practical significance of this type of coefficient in the study of the phenomena occasioned by short circuits. It is this comparatively restricted aspect of the general subject which is considered in the present paper.

Following conventional practise, these particular characteristic coefficients which express the factors of proportionality between reactive voltage and current, are referred to, generally, as reactances.

*Dependence of Reactance on Terminal Circuit.* Unlike a simple reactance, however, these reactances are not independent of the character of the terminal circuit. Thus, when negative phase-sequence voltage is applied directly at the terminals of a three-phase machine, the phase current contains a negative phase-sequence fundamental and a positive phase-sequence third harmonic. Neglecting the effect of the resistance of the closed rotor circuits as regards double frequency current, the per-unit value of the fundamental component of current with normal negative phase-sequence voltage applied is approximately

$$\frac{1}{2}\left(\frac{1}{x_d''}+\frac{1}{x_q''}\right) \qquad \textbf{(1)}$$

corresponding to a reactance:

$$x_2=\frac{2\,x_d''\,x_q''}{x_d''+x_q''}. \qquad \textbf{(2)}$$

If this voltage were applied through an external reactance, $x$, the total reactance of the circuit would be:

$$\frac{2\,(x_d''+x)\,(x_q''+x)}{x_d''+x+x_q''+x}.$$

Thus, the effective negative phase-sequence reactance of the machine would be:

$$x_2=\frac{2\,(x_d''+x)\,(x_q''+x)}{x_d''+x_q''+2\,x}-x$$

$$=\frac{2\,x_d''\,x_q''+x\,(x_d''+x_q'')}{x_d''+x_q''+2\,x}. \qquad \textbf{(3)}$$

If $x$ is sufficiently great this reactance becomes:

$$x_2=\frac{1}{2}\,(x_d''+x_q''). \qquad \textbf{(4)}$$

Physically, the effect of the external reactance is to force the current in the machine to be sinusoidal, and to permit the existence of a third harmonic voltage across each phase. This results in a change in the effective negative phase-sequence reactance of the machine. This change may be considerable. For instance, the ratio of the two extreme types of reactance given by equations (**2**) and (**4**) might be as high as five to one.[19]

In the case of sustained single-phase line-to-line short circuit, on the other hand, or in the equivalent case of fundamental voltage impressed from line-to-line, the per-unit *fundamental* component of current is shown by Doherty and Nickle to be:[20]

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[17] Three-phase machines are referred to. The armatures of single-phase machines may be regarded as three-phase armatures with one leg left idle in operation.

[18] The term *short-circuit ratio*, expressing the per-unit armature current on sustained short circuit due to the application of no-load field current, is an exception to this rule.

[19] In the case of the small machine employed in the tests illustrated in Doherty and Nickle's paper *Synchronous Machines IV* the negative phase-sequence coefficient is 0.40 when negative phase-sequence voltage is impressed directly, and is 1.99 when the voltage is impressed through a large reactance, or a ratio of five, based on the smaller quantity. This, however, is a very extreme case.

In machines of normal design, the ratio would be approximately,

| | |
|---|---|
| Water-wheel generators | 1.30 |
| Synchronous Motors and Condensers | 1.04 |
| Turbine Generators | 1.00 |

The exact difference in these two types of reactances is discussed in detail in Appendix D.

[20] This form follows from equation (**27b**) of the paper mentioned by substituting $x_D = 2\,x_d$, $x_D' = 2\,x_d''$, and $x_Q' = 2\,x_q''$.

$$\frac{\sqrt{3}\,e}{x_d + \sqrt{x_d''\,x_q''}}$$

where $e$ is the per-unit voltage before the short. Thus $e$ is also the per-unit value of the equivalent line-to-line voltage impressed. But, in the analysis provided by the method of symmetrical coordinates, this current is:

$$\frac{\sqrt{3}\,e}{x_d + x_2}. \qquad (5)$$

Thus, for the particular type of short-circuit under consideration, the effective negative phase-sequence reactance is

$$x_2 = \sqrt{x_d''\,x_q''} \qquad (6)$$

that is, the geometric average of $x_d''$ and $x_q''$. If, however, the short circuit is effected through an external reactance, $x$, per phase, the reactance of the complete circuit is:

$$\sqrt{(x_d'' + x)\,(x_q'' + x)}$$

and the effective reactance of the machine is:

$$x_2 = \sqrt{(x_d'' + x)\,(x_q'' + x)} - x \qquad (7)$$

Expanding (7) by the binomial theorem gives:

$$x_2 = x\left[1 + \frac{1}{2}\left\{\frac{x_d'' + x_q''}{x} + \frac{x_d''\,x_q''}{x^2}\right\} - \frac{1}{8}\left\{\frac{x_d'' + x_q''}{x} + \frac{x_d''\,x_q''}{x^2}\right\}^2 \ldots \text{etc.}\right] - x$$

When $x$ is sufficiently large this becomes

$$x_2 = \frac{1}{2}\,(x_d'' + x_q'') \qquad (8)$$

as in (4).

In practise short circuits are usually effected through some external reactance. For this reason, and in order to retain the principle that the reactance of a machine and any external reactance in series[21] is the sum of the machine and external reactances, it is desirable to normally regard the reactance of a machine, when referred to without qualification, as that obtaining with a large external reactance in each phase, or the reactance that obtains with fundamental *current* rather than voltage impressed. Thus, negative phase-sequence reactance is to be interpreted normally as the effective phase-sequence reactance with current rather than voltage impressed and, numerically, may be taken as the average of $x_d''$ and $x_q''$.

So far, it has been pointed out that the effective negative phase-sequence reactance of a synchronous machine varies with the nature of the circuit external to the machine. This effect, however, is not limited to the negative phase-sequence reactance, but applies, to a slight extent, to positive and zero phase-sequence reactances. Thus, when fundamental current is "impressed" on a synchronous machine, the rotor of which is moving normally, harmonic as well as fundamental terminal voltages are produced. If, however, the machine is supplied from an infinite bus these harmonic voltages are short-circuited. But an $n$th harmonic current of proper phase-sequence, taken in combination with a winding which does not exclude $n$th harmonic m. m. f., results in the rotation of this m. m. f., in synchronism with the poles. Also, with a salient pole machine, an $n$th harmonic m. m. f. over the pole can give rise to a flux of fundamental pitch, and thus generate fundamental voltage. It follows that if the harmonic voltages which exist with current impressed are short-circuited by impressing fundamental voltage at the terminals of the machine, the effect of the resulting harmonic currents will be to generate some fundamental voltage. This slightly modifies the proportion between positive phase-sequence current and voltage from the value which would obtain with current impressed at the machine terminals.

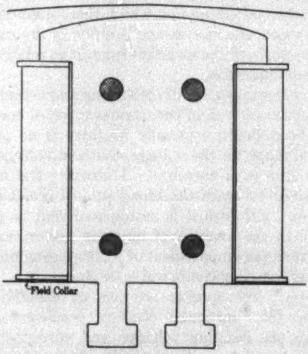

FIG. 6—30,000-KV-A. WATERWHEEL GENERATOR. ROTOR CIRCUITS: FIELD COLLAR

## DIVISION OF SYNCHRONOUS REACTANCE INTO ARMATURE REACTION AND LEAKAGE REACTANCE

*Armature reaction.* The synchronous reactance of a machine is ordinarily calculated as the sum of the armature reactance due to armature reaction flux, and the armature reactance due to leakage flux, but the exact line of demarcation between reactive and leakage flux has not always been very carefully drawn.

Originally, armature reaction was apparently considered equivalent merely to the action of a lumped coil moving along the armature surface and subtracting its ampere-turns directly from the ampere-turns on the pole. Later, it was realized that it was desirable to modify the effective amount of armature reaction to take account of the facts;—that the m. m. f. of armature reaction existed at the armature surface and, hence, a given amount of it did not have the same effect as if it were due to the field winding; and that the principal component of m. m. f., and the only one that is stationary with respect to the poles, is distributed sinusoidally along the armature surface.

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[21] When reactances are to be taken in parallel the principle is reversed. However, it is felt that usually the series principle is the more useful.

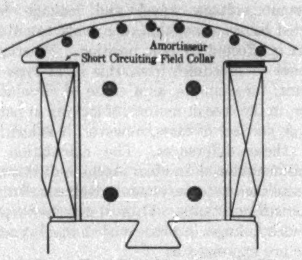

FIG. 7—150-KV-A. HIGH-SPEED SYNCHRONOUS MOTOR. ROTOR CIRCUITS: AMORTISSEUR, FIELD COLLAR

Thus, in recent theory, armature reaction is understood to refer to the space fundamental or stationary component of m. m. f. due to the armature. However, some question arises as to whether the term should be interpreted to apply to the total synchronous m. m. f., due to the armature, thus including the synchronous m. m. f. in the end-windings, or whether it should be limited so as to refer only to the m. m. f. along the stacked length of the machine.

Obviously, the answer to this question should depend on the relative value of each alternative as regards calculating the performance of the machine. But the chief purpose of separating out the voltage due to armature reaction from the total synchronous reactance drop is to consider separately those fluxes which can normally penetrate the rotor windings, and which can, under abnormal conditions, induce direct current or slip frequency in these circuits. Therefore, it appears logical that, in general, armature reaction should be taken to include all of the m. m. f. that is stationary with respect to the rotor, since, and especially in induction motors or turbo alternators, the end-winding m. m. f. can produce a flux which links the rotor circuits. Hence, this point of view, *i. e.*, that armature reaction exists in the end windings as well as along the stacked length of the machine, is favored by the authors.

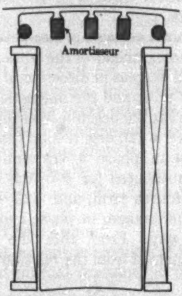

FIG. 8—240-KV-A. LOW-SPEED SYNCHRONOUS MOTOR. ROTOR CIRCUITS: AMORTISSEUR

However, from a practical point of view, the net effect of the armature reaction in the end-windings of a salient pole machine is usually negligible as far as regards the induction of flux in any of the rotor circuits. Consequently in the present state of the art, at least, it is legitimate to regard all the end-winding flux of salient pole machines as leakage flux.

In the case of turbo alternators, this assumption is less correct, although the action of the iron end-rings employed on these machines tends to reduce the mutual flux between armature and field, and, thus, lessen the degree of approximation involved. However, these machines have a relatively small leakage reactance, so that the error involved, practically, in treating end-flux as all leakage is small here also.

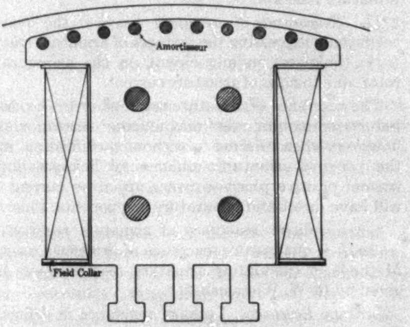

FIG. 9—25,000-KV-A. SYNCHRONOUS CONDENSER. ROTOR CIRCUITS: AMORTISSEUR, FIELD COLLAR

On the other hand, in the case of induction motors, there can exist a comparatively large amount of end-flux. Since a considerable part of this flux may be mutual with the rotor winding, the approximation that end-flux is all leakage cannot be satisfactorily employed.

Thus, on account of physical appropriateness, and to obtain consistency, it is desirable, normally, to consider all armature m. m. f. which is stationary with respect to the rotor as armature reaction. In practical computations, however, it is desirable, at present, to limit the term to the m. m. f. in the stacked length of the machine, except in the case of induction motors and special synchronous machines.

In addition to establishing the conception of *armature reaction* as denoting a particular type of m. m. f., it has appeared desirable to broaden the scope and application of the term so that it may apply not only to m. m. f. but also to fluxes and their linkages. Thus, it is proposed to characterize by the qualifying term *armature reaction* all those phenomena which depend upon the action of the synchronous component of armature m. m. f. In this way there are:

A. *M. m. f. of armature reaction*, or armature reaction proper; all the synchronous armature m. m. f.

B. *Flux or flux density of armature reaction;* that component of flux, or of flux density at any point of the air-gap or in the rotor, which is due to the armature reaction m. m. f.; under normal conditions, all that flux or flux density which is stationary with respect to the rotor.

C. *Linkages of armature reaction;* the linkages with any circuit on the armature, or rotor, of the fluxes of armature reaction.

D. *Reactances of armature reaction;* the reactive coefficients expressing the voltages of armature reaction (*i. e.*, linkages) in any circuit on the armature, or rotor, due to normal armature current.

The reactance of armature reaction, or in the case of induction motors, the magnetizing reactance, will, however, when referred to without qualification, mean the per-unit armature fundamental linkages due to normal positive phase-sequence armature current and will have direct and quadrature components, thus:

$x_{ad}$ = direct reactance of armature reaction

$x_{aq}$ = quadrature reactance of armature reaction.

Methods of calculating armature reaction have been given by R. W. Wieseman.[22]

*Leakage Reactance.* Leakage reactance is defined as that part of synchronous reactance which is not included in the reactance of armature reaction. Hence, there are two components

$$x_{ld} = x_d - x_{ad}$$

$$x_{ld} = x_q - x_{aq}.$$

They are the reactances due to the flux in the slots and to the flux produced by the moving harmonic of m. m. f., which latter is that flux in the air-gap or end-winding which is not normally stationary with respect to the poles. Actually, the flux due to the *n*th harmonic m. m. f. pulsates over the rotor at $\left(1 - \frac{1}{n}\right)$ times normal frequency and, therefore, is subject to the demagnetizing influence of the field winding and all other closed rotor circuits. Consequently, in determining the permeance[23] of the air-gap to *n*th harmonic m. m. f. the effect of these circuits should be considered. In practise, however, the rotor circuits are adjusted as far as possible so that this effect is small in order to eliminate losses in these windings.

Methods of calculating leakage reactance are given by Mr. P. L. Alger in a companion paper on this subject.

### THE IDEAL SYNCHRONOUS MACHINE

The ideal synchronous machine has a sinusoidal open-circuit voltage wave, and leakage reactance unaffected by rotor position, *i. e.*, only armature reaction flux is affected by pole position. Practically, the divergence of machines from this ideal type is often important; for example, as a cause of circulating currents, or, in the case of motors, of locking at part speed. In a large number of cases, however, it is legitimate to neglect these differences. The calculation of the electrical behavior of an ideal machine of this type can be accomplished in terms of a relatively small number of characteristic constants. Thus, it may be shown[24] that the per-unit linkages in phase *a* of an ideal synchronous machine are expressed as

$$\psi a = I_d \cos\theta - I_q \sin\theta - \frac{x_0}{3}(i_a + i_b + i_c)$$

$$- \frac{x_d + x_q}{3}\left[i_a - \frac{i_b + i_c}{2}\right]$$

$$- \frac{x_d - x_q}{3}\Big[i_a \cos(2\,\theta) + i_b \cos(2\,\theta - 120)$$

$$+ i_c \cos(2\,\theta + 120)\Big] \qquad \textbf{(10)}$$

where,

$i_a$, $i_b$, and $i_c$ are the instantaneous currents in phases *a*, *b*, and *c*.

$I_d$ is the nominal voltage, or per-unit rotor current in the direct axis.

$I_q$ is the nominal voltage, or per-unit rotor current in the quadrature axis, ahead of the poles.

$\theta$ = electrical degrees in direction of normal rotation between axis of poles and the magnetic axis of phase *a*.

Axis of phase *b* is 120 deg. ahead of the axis of phase *a*.

Axis of phase *c* is 120 deg. behind the axis of phase *a*.

The linkages in phase *b* are similar except that $(\theta - 120)$ is substituted for $\theta$ in the first two terms, $i_b$ for $i_a$ in the fourth term, and $(120 - \theta)$ for $\theta$ in the fifth term. The linkages in phase *c* are obtained in a corresponding way. From this, the voltage of any phase can be obtained from the relation

$$e_a = \frac{d\,\psi_a}{d\,t} - r\,i_a \qquad \textbf{(11)}$$

In order to determine the reactance between the armature and rotor, it is of great benefit to resolve the armature quantities under consideration with respect to the two axes of symmetry of the poles, a procedure introduced by Blondel and further developed by Arnold, and Doherty and Nickle.

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[22] Reference (5).

[23] Reference (8).

[24] Reference (14).

To this end, and in analogy with their recognized significance under steady conditions of operation, let the direct and quadrature components of current at any instant, and under any condition of operation, be taken equal to the instantaneous amplitudes of the direct and quadrature components of armature m. m. f. It may be shown[25] that, at any instant, the magnitudes of these m. m. fs. are equal to the quantities

$$i_d = \frac{2}{3}\left[i_a \cos\theta + i_b \cos(\theta - 120) + i_c \cos(\theta + 120)\right] \quad \textbf{(12)}$$

$$i_q = \frac{2}{3}\left[i_a \sin\theta + i_b \sin(\theta - 120) + i_c \sin(\theta + 120)\right]$$

The currents, $i_d$ and $i_q$, then determine the reaction of the armature on the rotor at any instant. In general, there will be more than one rotor circuit. Consider, however, any particular circuit, say circuit $h$ of the direct axis; that is, circuit $h\,d$. There will be factors of proportionality between the linkages, $\Psi_{hd}$, in this circuit, the currents in every other rotor circuit in the direct axis, and the instantaneous direct component of armature current. Thus, there is

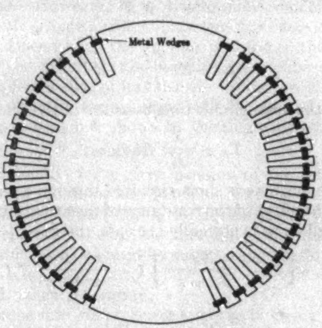

FIG. 10—10,000-KV-A. TURBO ALTERNATOR. ROTOR CIRCUITS: ROTOR IRON, METAL WEDGES

$$\Psi_{hd} = X_{hfd}\, I + X_{h1d}\, I_{1d} + \;.\;.\;.\;.\;.\;.\;.\;.\;.$$
$$+ X_{hhd}\, I_{hd} + \;.\;.\;.\;.\; X_{hnd}\, I_{nd} - X_{hmd}\, i_d \quad \textbf{(13)}$$

where

$I$ = per-unit field current

$I_{hd}$ = per-unit current in circuit $h$ of the direct axis

$X_{hfd}$ = per-unit mutual reactance of field with circuit $h\,d$

$X_{hnd}$ = per-unit mutual reactance of circuit $h\,d$ with circuit $n\,d$.

$X_{hmd}$ = per-unit mutual reactance of armature with circuit $h\,d$.

Similar relations exist in the quadrature axis except that field current is not involved.

If there is only one rotor circuit, equation (**13**) becomes merely

$$\Psi = X\, I - X_m\, i_d$$

in which $\Psi$, $X$, $X_m$, and $I$ refer to this circuit.

In order to retain the valuable principle that the per-unit nominal voltage is equal to the total rotor current, it is desirable to define unit current in any circuit as that current which acting by itself produces normal space fundamental flux at the armature surface. In this way the nominal voltage at any instant is always to be identified as the instantaneous rotor current. Thus, in the direct axis, as

$$I_d = I + I_{1d} + I_{2d} + \;.\;.\;.\; + I_{nd} \quad \textbf{(14)}$$

*Transient Reactance.* In analogy with the procedure employed in determining the effect of the armature circuit on the rotor, it is desirable to establish the conception of instantaneous direct and quadrature components of armature linkages. If these components are defined as

$$\psi_d = \frac{2}{3}[\psi_a \cos\theta + \psi_b \cos(\theta - 120) + \psi_c \cos(\theta + 120)] \quad \textbf{(15)}$$

$$\psi_q = -\frac{2}{3}[\psi_a \sin\theta + \psi_b \sin(\theta - 120) + \psi_c \sin(\theta + 120)]$$

it may be verified that the simple relations, which obtain between armature linkages and armature and rotor currents under steady conditions, now hold at any instant. That is, under all conditions,

$$\begin{aligned}\psi_d &= I_d - x_d\, i_d \\ \psi_q &= I_q - x_q\, i_q\end{aligned} \quad \textbf{(16)}$$

Transient reactance will then be the constant of proportionality between $\psi$ and $i$ when $i$ is suddenly impressed. Thus, if $\Delta\,\psi_d$ is the sudden change in $\psi_d$ when a current $\Delta\, i_d$ is suddenly impressed, there is

$$x_d' = -\frac{\Delta\,\psi_d}{\Delta\, i_d} \quad \textbf{(17)}$$

But, $\Delta\,\psi_d = \Delta\, I_d - x_d\,\Delta\, i_d$

where $\Delta\, I_d$ is the corresponding increase in direct axis rotor current. Therefore,

$$x_d' = x_d - \frac{\Delta\, I_d}{\Delta\, i_d} \quad \textbf{(18)}$$

and similarly in the quadrature axis. The value of $\Delta\, I_d$ may be found by solving the $n$ equations

$$\Psi = \Psi_{1d} = \Psi_{2d} = \;.\;.\;.\;.\; \Psi_{nd} = 0 \quad \textbf{(19)}$$

subject to the conditions $i_d = \Delta\, i_d$. $\Delta\, I_q$ may be found similarly. We shall only consider in detail here the case of a single rotor circuit. The equations (**19**) become in this case merely

$$\Psi = X\,\Delta\, I - X_m\,\Delta\, i_d = 0$$

from which it follows that, in this case,

$$x_d' = x_d - \frac{X_m}{X} \quad \textbf{(20)}$$

where $X_m$ is the mutual reactance of the main field wind-

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25. Reference (14).

ing with respect to the armature, and $X$ is the total field reactance.

*Calculation of Rotor Reactances.* Before calculating these quantities in per-unit terms it is necessary to decide on an appropriate value of normal or unit linkages. It has been found convenient to specify normal linkages in each rotor circuit as the product of normal flux by the number of series turns in the circuit. On this basis it is shown in Appendix G that, for any rotor circuit $h$,

$$X_{hm} = \frac{A_{(0)}}{F_{h\,(0)}} \tag{21}$$

where,

$A_{(0)} = 2.12 \times$ (effective full-load armature ampere-turns per pole, per phase).

$F_{h\,(0)}$ = normal no-load ampere-turns of circuit $h$ with no saturation.

Thus, the determination of the mutual reactances of $X_{mh}$ can be reduced to the determination of no-load excitation ampere-turns in each rotor circuit.

The self and mutual rotor reactances at present require flux plots for their determination, except in the case of the total field reactance.

As shown in Appendix F, the latter is given by the expression

$$X = K_\phi + \frac{F_{(0)}}{\phi_{(0)}}\, l\, L \tag{22}$$

where $K_\phi$ and $L$ are given by formulas and curves in Doherty and Shirley's 1918 paper on reactances, $l$ is the stacked length of the machine, and $\phi_{(0)}$ is normal no-load armature flux. The transient reactance of a machine with no additional rotor circuits is then given as

$$x_d' = x_d - \frac{A_{(0)}}{F_{(0)}}\,\frac{1}{K_\phi + \dfrac{F_{(0)}}{\phi_{(0)}}\, l\, L} \tag{23}$$

*Equivalent Circuits and Field Leakage Reactance.* This general subject is treated mathematically in Appendix E. It is shown that any number of equivalent circuits can be constructed to represent the relation between armature and rotor currents and linkages. Of the various circuits which may be so constructed there is one in which the armature branch is $x_{ld}$, and the magnetizing branch is $x_{ad}$. The field branch of this particular circuit has been referred to as the field leakage reactance, and is denoted by $X_l$.[26] It is shown in Appendix E that $X_l$ may be expressed in terms of the quantities already described by the relation,

$$X_l = x_{ad}\left(\frac{x_{ad}\, X}{X_m} - 1\right) \tag{24}$$

*Field Voltage.* It sometimes is desirable to define normal field voltage as the voltage which will just force normal current through the resistance of the field, but in order to obtain symmetry with the equations for armature voltage a different procedure is here employed. In the following, normal voltage of any rotor circuit is that voltage which would exist in this circuit if normal flux changed through it at normal frequency. Normal resistance is then the ratio of normal $I\,R$ drop to this voltage. In this way the per-unit voltage of any field circuit, say $h\,d$, is

$$E_{hd} = \frac{d\,\Psi_{hd}}{d\,t} + R_{hd}\, I_{hd} \tag{25}$$

while for the field circuit proper there is

$$E = \frac{d\,\Psi}{d\,t} + R\,I \tag{26}$$

*Decrements.* Only the case of a machine with the field as the only rotor circuit will be considered. In this case, if the armature is open-circuited, there is

$$\Psi = X\,I$$

and

$$E = X\,\frac{d\,I}{d\,t} + R\,I$$

so that the open-circuit time-constant of the field is

$$T_0 = \frac{X}{R} \text{ (radians)} \tag{27}$$

If the machine is short-circuited through a reactance $x$, and the effect of the resistance of the armature circuit is negligible, as is normally the case, there is

$$\Psi = \left[X - \frac{X_m}{x_d + x}\right] I = \frac{x_d' + x}{x_d + x}\, X\, I$$

$$E = \frac{x_d' + x}{x_d + x}\, X\, \frac{d\,I}{d\,t} + R\,I$$

so that the time-constant of the field, in this case, is

$$T = \frac{x_d' + x}{x_d + x}\, T_0 \tag{28}$$

The time-constant on dead short-circuit is

$$T_0' = \frac{x_d'}{x_d}\, T_0 \tag{29}$$

The effect of armature resistance, or of machines operating in parallel, is to modify these results in a complicated way which will not be considered here.

If, as is ordinarily the case, the resistance of the rotor circuit is negligible, the time-constant of the direct current in the armature depends upon the inductance of the armature to direct current in the same way as the time-constant of direct current in the field depends on the inductance of the field to direct current. The inductance of the armature to direct current is, however, the average of $x_d''$ and $x_q''$, and is thus equal to the negative phase-sequence reactance. Thus the time-constant for the d-c. component in the armature is simply

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[26] Reference (6).

$$\tau = \frac{x_2}{r} \text{ (radians)}$$

as stated in Part I.

### ACKNOWLEDGMENTS

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## Appendix A

### APPLICATION OF THE PRINCIPLE OF SUPERPOSITION TO THE ANALYSIS OF SYNCHRONOUS MACHINES

In a synchronous machine, as in a static device, the flux density at any point will be in linear relation to the total number of currents in every circuit of the machine, providing saturation and hysteresis are neglected. However, in a synchronous machine the factors of proportionality between flux density and current depend upon the angular position of the rotor. Thus, if the circuits in the machine are numbered 1, 2, etc., the component of flux density in a given direction at any point of the machine will be related to the currents in a manner shown by the following equation:

$$\beta = f_1(\theta)\, i_1 + f_2(\theta)\, i_2 + \ldots \text{ etc.}$$

Consequently, for a given position of the rotor, the flux at any point in the machine may be found by superposing the fluxes due to the current in every circuit acting separately. Also, the flux due to the current in any circuit may be found by superposing the fluxes due to any components into which this current may be resolved, taken separately.

The same rule will of course apply to linkages. Thus, the linkages in circuit 1 will be represented as

$$\psi_1 = \lambda_{11}(\theta)\, i_1 + \lambda_{12}(\theta)\, i_2 + \ldots \text{ etc.}$$

where $\lambda_{11}$ is the self-inductance of circuit 1, and $\lambda_{12}$ is the mutual inductance of circuit 1 with respect to circuit 2. The voltage in circuit 1 is then

$$e_1 = r_1 i_1 + \frac{d\psi_1}{dt}$$

$$= \left(r_1 + \frac{d\lambda_{11}(\theta)}{d\theta}\frac{d\theta}{dt}\right) i_1 + \lambda_{11}(\theta)\frac{di_1}{dt} + \frac{d\lambda_{12}(\theta)}{d\theta}\frac{d\theta}{dt} i_2$$

$$+ \lambda_{12}(\theta)\frac{di_2}{dt} + \ldots \text{ etc.}$$

But, since if $i = i_x + i_y$

$$\frac{di}{dt} = \frac{di_x}{dt} + \frac{di_y}{dt}$$

it follows that, for a given *position* and *speed* of the rotor, the voltage in any circuit of the machine may be found by superposing the voltages due to the current in every other circuit acting separately. Also, under the same conditions, voltage due to the current in any circuit may be found by superposing the voltages due to any components into which this current may be resolved.

To illustrate, the armature voltage due to a field current $I$, and an armature current $i$, may be found as the sum of the armature voltages due to the currents $I$ and $i$ acting separately. That is, the voltage under load may be found by subtracting from the no-load voltage corresponding to the existing field current, the voltage due to the impedance drop caused by the armature current. Or, the voltage due to a current

$$i = i_a \sin(t + \alpha)$$

can be found by superposing the voltages due to currents

$$i_x = i_a \cos\alpha \sin t$$

and,

$$i_y = i_a \sin\alpha \cos t$$

acting alone.

So far it has merely been pointed out under what conditions the voltages due to a given current distribution can be found by superposing the voltages due to any components of the distribution. Suppose, however, that a given distribution of voltage is impressed at the machine terminals. Let this distribution be characterized by the symbol $e(t)$, and let $e_x(t)$ and $e_y(t)$ be component distributions into which $e(t)$ may be resolved so that $e(t) = e_x(t) + e_y(t)$. Let the currents due to these distributions be $i(t)$, $i_x(t)$, and $i_y(t)$. Then there must be

$$i(t) = i_x(t) + i_y(t)$$

since this result fulfills all the conditions imposed by the differential equations and terminal conditions of each circuit of the machine, provided that the position of the rotor as a function of time, $\theta(t)$, is the same with $e(t)$, $e_x(t)$, and $e_y(t)$ impressed.

Thus, it follows that the current distribution due to a given distribution of armature voltage may be found by superposing the current distributions due to any components into which the voltage distribution may be resolved, provided that the motion of the rotor, as a function of time, is the same for the components as for the resultant.

For example, if a machine is supplying current to a reactor and is then short-circuited, the current at any time after the short circuit may be found by superposing on the initial current distribution the fictitious currents which would be due to the application of a negative voltage at the point of short circuit. This negative voltage is equal and opposite to that which would have existed at the point of short circuit had the short circuit not occurred, and it is assumed to be applied with the machine unexcited.

On the other hand, if the machine is supplying a kilowatt load, it would be only possible to calculate the currents at the instant of short circuit in such manner. This is because of the fact that generally, in this case, the motion of the rotor would be different before and after the short circuit on account of the change in load effected by the short circuit. In the first instant, however, the inertia of the rotor would prevent a change in its motion.

When current is impressed on the open circuits of a machine, in which closed circuits also exist, the same limitations apply as in the case for voltage. In both events the currents and voltages due to the impressed quantities depend on the complete variation in time of those quantities. Superposition is still legitimate, subject to the condition that the motion is the same for the components as for the resultant.

The general statement of the possibility of superposition is, then, that *for a given motion or position* of the rotor, the currents and voltages in any part of the machine, due to any currents or voltages impressed at its terminals, may be found by superposing the effects that would result from the action of each taken separately.

## Appendix B

### REPLACING THE EFFECT OF INDUCED FIELD CURRENTS BY EMPLOYING TRANSIENT INSTEAD OF SYNCHRONOUS REACTANCES

Equation (**10**), of Part II, gives the complete expression for the phase linkages of a synchronous machine under all conditions of operation. However, in the case of rapidly changing or suddenly impressed currents, there is a definite relation between the currents in the field and armature circuits.[27] As a consequence, the field current terms may be replaced by terms involving armature currents.

Thus, if the field circuit is closed, and the effects of a given armature current are to be calculated

a. only in the first instant after their sudden application,

b. under sustained conditions of such a nature that all m. m. fs. over the poles are pulsating, or moving at sufficient speed that the demagnetizing action of the rotor circuits is practically complete,

it is merely necessary to substitute $x_d''$ and $x_q''$ or $x_d'$ and $x_q'$ for $x_d$ and $x_q$ in order to eliminate the terms $I_d$ and $I_q$.

The linkages in phase *a* thus become

$$\psi_a = -\frac{x_0}{3}(i_a + i_b + i_c) - \frac{x_d'' + x_q''}{3}\left[i_a - \frac{i_b + i_c}{2}\right]$$

$$-\frac{x_d'' - x_q''}{3}\Big[i_a \cos(2\,\theta) + i_b \cos(2\,\theta - 120)$$

$$+ i_c (\cos(2\,\theta + 120)\Big] \qquad \mathbf{(1b)}$$

$x_d'$ and $x_q'$ replace $x_d''$ and $x_q''$ when the m. m. f. over the poles is

a. Suddenly impressed, but steady thereafter, and it is desired to determine the effects of currents after the currents in the "additional rotor circuits" have died away.

b. Alternating so slowly that the demagnetizing action of the "additional rotor circuits" is slight.

But if, with closed circuits on the rotor, the armature currents are sustained and of such a nature that the armature m. m. f. is stationary and steady over the poles, $x_d$ and $x_q$ are used as before.

Finally, if there are closed circuits on the rotor, but neither of the above conditions is fulfilled, it is generally possible to divide the currents into two parts; first, those which meet sub-transient or transient reactance, and second, those which meet synchronous reactance. The appropriate factor is then used with each type of current. For example, a single-phase line-to-line current

$$i_a = -i_b = i_0 \cos t$$

is resolvable into positive and negative phase-sequence components as

$$i_a = \frac{1}{\sqrt{3}} i_0 [\cos(t - 30) + \cos(t + 30)] = i_0 \cos t$$

$$i_b = \frac{1}{\sqrt{3}} i_0 [\cos(t - 150) + \cos(t + 150)] = -i_0 \cos t$$

$$i_c = \frac{1}{\sqrt{3}} i_0 [\cos(t + 90) + \cos(t - 90)] = 0 \qquad \mathbf{(2b)}$$

For normal motion of the rotor, the positive phase-sequence component of current meets synchronous reactance, and the negative phase-sequence meets sub-transient reactance. Thus,

$$\psi_a = -\frac{i_0}{3}\left[\begin{array}{l} \dfrac{x_d + x_q}{2}\cos(t - 30) \\ + \dfrac{x_d - x_q}{2}\cos(t + 2\,\theta_0 + 30) \\ + \dfrac{x_d'' + x_q''}{2}\cos(t + 30) \\ + \dfrac{x_d'' - x_q''}{2}\cos(3\,t + 2\,\theta_0 + 30) \end{array}\right] \qquad \mathbf{(3b)}$$

## Appendix C

### SIGNIFICANT ROTOR CIRCUITS IN ADDITION TO THE FIELD

The principal circuits in the rotor of a machine, besides the field winding proper, which are capable of significantly affecting the behavior of the machine under practical operating conditions, are listed in Table III.

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[27] That is, $I_d = (x_d - x_d'')\,i_d$ and $I_q = (x_q - x_q'')\,i_q$.

TABLE III

| Type of Machine | Significant rotor circuits in addition to field |
|---|---|
| Water-wheel Generators | Amortisseur, if used. |
| Synchronous Motors and Condensers. | Field collars, if used.<br>Spider, unless laminated. |
| Turbine Generators | Metal Wedges<br>Rotor Iron, unless laminated. |

Figs. 6 to 10 show these circuits pictorially for representative machines of each type.

## Appendix D

### THE NEGATIVE PHASE-SEQUENCE REACTANCE OF A SYNCHRONOUS MACHINE WITH NEGATIVE PHASE-SEQUENCE VOLTAGE IMPRESSED

With normal negative phase-sequence current impressed on the terminals of a machine the phase currents are,

$$i_a = \cos t$$
$$i_b = \cos (t + 120)$$
$$i_c = \cos (t - 120)$$

It follows from equation (**10**), of Part II, and from the fact that all the resultant fluxes are varying rapidly over the rotor,[28] that the flux linkages in each phase are, under these circumstances,

$$\psi_a = \frac{x_d'' + x_q''}{2} \cos t + \frac{x_d'' - x_q''}{2} \cos (2\,\theta + t) \qquad \textbf{(1d)}$$

$$\psi_b = \frac{x_d'' + x_q''}{2} \cos (t + 120) + \frac{x_d'' - x_q''}{2} \cos (2\,\theta + t - 120) \qquad \textbf{(2d)}$$

$$\psi_c = \frac{x_d'' + x_q''}{2} \cos (t - 120) + \frac{x_d'' - x_q''}{2} \cos (2\,\theta + t + 120) \qquad \textbf{(3d)}$$

The variation in linkages will give rise to a voltage of fundamental frequency and a harmonic of $(2\,d\,\theta/d\,t + 1)$ times fundamental frequency. For normal motion of the rotor these voltages will be fundamental and third harmonic of which the fundamental may be found by analyzing the voltage wave over one cycle. However, if the speed of the rotor is not exactly normal, the third harmonic in the terminal voltage will pulsate at the slip frequency.

If normal third harmonic positive phase-sequence current is impressed, *i. e.*, if

$$i_a = \cos (3\,t + \alpha)$$
$$i_b = \cos (3\,t - 120 + \alpha)$$
$$i_c = \cos (3\,t + 120 + \alpha)$$

the phase linkages become,

$$\psi_a = \frac{x_d'' + x_q''}{2} \cos (3\,t + \alpha) + \frac{x_d'' - x_q''}{2} \cos (2\,\theta - 3\,t - \alpha) \qquad \textbf{(4d)}$$

$$\psi_b = \frac{x_d'' + x_q''}{2} \cos (3\,t - 120 + \alpha) + \frac{x_d'' - x_q''}{2} \cos (2\,\theta - 3\,t - 120 - \alpha) \qquad \textbf{(5d)}$$

etc.

If fundamental negative phase-sequence voltage is maintained at the armature terminals, and if the resistance of the armature is negligible, the armature linkages will also be negative phase-sequence. This will require that both negative phase-sequence fundamental and positive phase-sequence third-harmonic currents exist, having a definite ratio to each other. Thus, let $i_{2(1)}$ be the magnitude of the negative phase-sequence *fundmental* current, and $i_{1(3)}$ be the magnitude of the positive phase-sequence *third-harmonic* current. Also, suppose that the two are acting together, and let $\theta = \theta_0 + t$. Then, combining equations (**1d**) and (**4d**),

$$\psi_a = i_{2(1)} \frac{x_d'' + x_q''}{2} \cos t + i_{1(3)} \frac{x_d'' + x_q''}{2} \cos (3\,t + \alpha) + i_{2(1)} \frac{x_d'' - x_q''}{2} \cos (3\,t + 2\,\theta_0) + i_{1(3)} \frac{x_d'' - x_q''}{2} \cos (2\,\theta_0 - t - \alpha) \qquad \textbf{(6d)}$$

If, $\alpha = 2\,\theta_0$

and, $$i_{2(1)} \frac{x_d'' - x_q''}{2} = - i_{1(3)} \frac{x_d'' + x_q''}{2} \qquad \textbf{(7d)}$$

$\psi_a$ will contain only a fundamental component, *i. e.*,

$$\psi_a = i_{2(1)} \left[ \frac{x_d'' + x_q''}{2} - \frac{(x_d'' - x_q'')^2}{2\,(x_d'' + x_q'')} \right] \cos t$$

$$= i_{2(1)} \frac{2\,x_d''\,x_q''}{x_d'' + x_q''} \cos t \qquad \textbf{(8d)}$$

If $\psi_a = \cos t$

then $$i_{2(1)} = \frac{1}{2} \left( \frac{1}{x_d''} + \frac{1}{x_q''} \right)$$

and $$i_{1(3)} = - \frac{1}{2} \left( \frac{1}{x_d''} + \frac{1}{x_q''} \right) \left( \frac{x_d'' - x_q''}{x_d'' + x_q''} \right)$$

But under the conditions specified,

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[28] See Appendix B.

$$\psi_b = \cos(t + 120), \quad \psi_c = \cos(t - 120),$$

so that the current distribution,

$$i_a = \frac{1}{2}\left(\frac{1}{x_d''} + \frac{1}{x_q''}\right)\left[\cos t - \frac{x_d'' - x_q''}{x_d'' + x_q''}\cos(3t + 2\theta_0)\right] \qquad \textbf{(9d)}$$

$$i_b = \frac{1}{2}\left(\frac{1}{x_d''} + \frac{1}{x_q''}\right)\left[\cos(t - 120) - \frac{x_d'' - x_q''}{x_d'' + x_q''}\cos(3t + 2\theta_0 - 120)\right] \qquad \textbf{(10d)}$$

$$i_c = \frac{1}{2}\left(\frac{1}{x_d''} + \frac{1}{x_q''}\right)\left[\cos(t + 120) - \frac{x_d'' - x_q''}{x_d'' + x_q''}\cos(3t + 2\theta_0 + 120)\right] \qquad \textbf{(11d)}$$

is just adequate to give rise to balanced normal negative phase-sequence terminal voltage. It follows that the application of balanced normal negative phase-sequence voltage will give rise to a fundamental negative phase-sequence current of amount

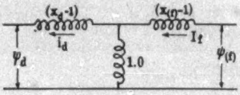

FIG. 11—EQUIVALENT CIRCUIT OF SYNCHRONOUS MACHINE DIRECT AXIS, MAIN FIELD ONLY

$$\frac{1}{2}\left(\frac{1}{x_d''} + \frac{1}{x_q''}\right)$$

The voltage may be applied either from line-to-line or from line-to-neutral.

## Appendix E

### CONSTRUCTION OF EQUIVALENT CIRCUITS: CONCEPT OF FIELD LEAKAGE REACTANCE

Consider a machine without any "additional rotor circuits." The equations relating per-unit armature and field linkages are, in this case:

$$\psi_d = I - x_d i_d \qquad \textbf{(1e)}$$

$$\Psi = X I - X_m i_d \qquad \textbf{(2e)}$$

The second equation may be put in the form,

$$\Psi_{(f)} = X_{(f)} I - i_d \qquad \textbf{(3e)}$$

where,

$$\Psi_{(f)} = \frac{\Psi}{X_m} \qquad \textbf{(4e)}$$

$$X_{(f)} = \frac{X}{X_m} \qquad \textbf{(5e)}$$

But, equations (**1e**) and (**3e**) are satisfied by the equivalent circuit of Fig. 11.

This circuit also holds good when the linkages $\Psi_{(f)}$ are determined by an external circuit such as an impedance, for example, a reactance and resistance in series. Thus, it is possible to calculate the power factor of a current of any frequency induced in the field, or to determine the effect of external field reactance, etc.

The field voltage equation is

$$E_{(f)} = \frac{d}{dt}\Psi_{(f)} + R_{(f)} I$$

where $E_{(f)} = \dfrac{E}{X_m}$ and $R_{(f)} = \dfrac{R}{X_m}$.

Reactance and resistance of the field circuit are, of course, to be calculated in per-unit and divided by $X_m$. Normal or per-unit resistance is the product of normal field current and resistance in ohms, divided by the voltage due to unit rate of change of normal flux linkages.

While the circuit just discussed is perfectly practical, it is not at all the only circuit that can be constructed, nor is it in every way the best, since it may involve negative reactances. These latter, while not inconvenient mathematically, are not entirely satisfactory from a physical standpoint.

A particular circuit previously employed[29] is that in which the armature branch of the equivalent circuit is made equal to the leakage reactance of the armature. In this case write:

$$\psi_d = A\left[\frac{I}{A}\right] - x_d i_d \qquad \textbf{(6e)}$$

$$B\Psi = A B X\left[\frac{I}{A}\right] - B X_m i_d \qquad \textbf{(7e)}$$

where $A$ and $B$ are arbitrary factors to be determined in such a way that $i_d$ and $\dfrac{I}{A}$ can be employed in the equivalent circuits. Then, it is necessary that

$$x_d - A = x_l \qquad \textbf{(8e)}$$

or,

$$A = x_d - x_l = x_{ad}$$

But, also there must be, on account of the nature of the equivalent circuit:

$$A = B X_m \qquad \textbf{(9e)}$$

$$B = \frac{A}{X_m} = \frac{x_{ad}}{X_m}. \qquad \textbf{(10e)}$$

The equations may then be written:

$$\psi_d = x_{ad} I_{[f]} - x_d i_d \qquad \textbf{(11e)}$$

$$\Psi_{[f]} = X_{[f]} I_{[f]} - x_{ad} i_d \qquad \textbf{(12e)}$$

where,

$$I_{[f]} = \frac{I}{x_{ad}} \qquad \textbf{(13e)}$$

$$\Psi_{[f]} = \frac{x_{ad}}{X_m}\Psi \qquad \textbf{(14e)}$$

---

[29] Reference (6).

$$X_{[f]} = \frac{(x_{ad})^2}{X_m} X \qquad \textbf{(15e)}$$

The equivalent circuit in this case is shown in Fig. 12. In this case the field voltage equation is

$$E_{(f)} = \frac{d}{d\,t} \Psi_{[f]} + R_{[f]} I_{[f]}$$

where $E_{[f]} = \dfrac{x_{ad}}{X_m} E$ and $R_{[f]} = \dfrac{x_{ad}}{X_m} R$

The term $X_{[f]} - x_{ad}$ has been referred to as field leakage reactance—thus,

$$X_l = X_{[f]} - x_{ad} = x_{ad} \left[ \frac{x_{ad}}{X_m} - 1 \right] = \frac{x_{ad}}{X_m} [x_{ad} - X_m] \qquad \textbf{(16e)}$$

The formula for transient reactance may be obtained by shorting the field side of the equivalent circuit. Referring to Fig. 12 this gives:

$$x_d' = x_d - 1 + \frac{(X_{(f)} - 1)}{X_{(f)}} = x_d - \frac{1}{X_{(f)}} = x_d - \frac{X_m}{X} \qquad \textbf{(17e)}$$

or in terms of field leakage reactance

$$x_d' = x_l + \frac{X_l\, x_{ad}}{X_l + x_{ad}} \qquad \textbf{(18e)}$$

The form $\left( x_d - \dfrac{X_m}{X} \right)$ is probably the easiest for calculation since;

$x_d$ is calculated by standard methods.

$X_m$ is calculated from a knowledge of no-load normal field current.

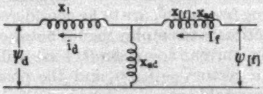

Fig. 12—Equivalent Circuit of Synchronous Machine, Direct Axis, Main Field Only

$X$ may be calculated without great difficulty. It is merely the ratio of the total field linkages to the linkages the field would enclose if normal space fundamental armature flux linked all of the field turns.

The construction of equivalent circuits when additional rotor circuits are to be considered is more difficult than in the simple case discussed and will not be treated here.

## Appendix F

### Calculation of Total Field Reactance

The calculation of total field reactance, *i. e.*, the quantity or quantities $X$, is conveniently accomplished by considering separately the fluxes at the armature surface, in the slots or inter-polar space, and at the ends of the poles. This corresponds to the division of armature leakage into air-gap, slot, and end leakage. The reactance $X$ is then expressible as the sum of three factors relating to the armature, inter-polar space, and pole ends respectively. Thus:

$X$ = Armature factor + inter-polar, or slot-factor + end factor.[30]

*Armature Factor.* That component of flux, due to current in any field circuit, which enters the armature surface will be assumed to link all of that circuit, a condition which, it happens, is very generally fulfilled. Then the armature factor in field reactance, expressed as a per-unit quantity, is the ratio of the total flux to the space fundamental component of flux entering the armature along one pole pitch. This factor was first employed by Doherty and Shirley in their paper on Reactance,[30] and has received the designation $K_\phi$. As pointed out by them, it is capable of being expressed as the sum of the per-unit harmonics of flux, due to normal current in the circuit under consideration, divided by the order of the harmonic. Thus:

$$K_\phi = 1 + \frac{k_3}{3} + \frac{k_5}{5} + \cdot \quad \cdot \quad \cdot \quad \cdot + \frac{k_n}{n}$$

where the corresponding per-unit flux density wave is:

$$\beta = 1 + k_3 \sin 3\,\gamma + k_5 \sin 5\,\gamma + \ldots \text{ etc.,}$$

$\gamma$ being the electrical angle measured from the quadrature axis of the machine.

It is interesting to realize, then, that harmonics in the no-load flux wave of a machine are of the nature of leakage flux. This leakage flux can, however, be positive or negative according to whether the wave of no-load flux is flat-topped or peaked. This would be indicated by negative constants in the above equation. Charts for determining $K_\phi$ for ordinary field windings are available in the above mentioned paper on Reactance.

*Interpolar, or Slot, and End Factors.* These factors comprise the field linkages due respectively to all the flux in the stacked length of the machine that does not penetrate the armature surface and to all the end-flux.[31] A formula for the field-flux linkages of salient-pole machines, due to flux which does not penetrate the armature surface, has been given by Doherty and Shirley.[32] Using the quantity $L$ given in formula **(33a)** of that paper, the inter-polar and end factor becomes equal to:

$$\frac{N\, I_{(0)}\, L\, l}{\phi_{(0)}}$$

Where $I_{(0)}$ = no-load field current in amperes

$\phi_{(0)}$ = no-load space fundamental flux per pole

$l$ = gross stacked length of core.

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[30] Reference (10) p. 1242.

[31] More strictly, all the end-flux which is not space fundamental at the armature winding.

[32] Reference (10), p. 1279.

Thus, there is:

$$X = K_{\phi} + \frac{N\, I_{(0)}\, L\, l}{\phi_{(0)}}$$

## Appendix G

### RELATION BETWEEN $X_m$ AND NO-LOAD EXCITATION CURRENT

Ordinarily, the leakage reactance of a machine does not have a transient value perceptibly different from its sustained one because the currents induced in the various rotor circuits by the leakage fluxes are sensibly reactive in character, *i. e.*, are nearly out of phase with the voltage producing them. Consequently, it is possible to neglect the changes in leakage reactance with method of application of current and to regard all the change that is necessary to account for the difference in synchronous and transient reactance as being due to the difference in the reactances of armature reaction in the two cases. Therefore, in calculating the values of the constants $X_m$, $X_{m1d}$, etc., it is only necessary to consider the flux linkages of armature reaction, that is, the flux linkages due to the space fundamental component of armature m. m. f.

But the effect of normal space fundamental m. m. f. acting in one axis of the rotor is just two-thirds[33] of the effect of the maximum value of normal phase current. That is, if $i_{(0)}$ is the current flowing in a single-phase winding when the rotor is stationary and its axis in question is directly in line with the axis of magnetization of the excited armature phase, the effect of normal space fundamental m. m. f. is $\frac{2}{3}\, i_{(0)}$.

Now consider any rotor circuit, for example, circuit *h*. The linkages in this circuit, due to a current of normal peak value $i_{(0)}$ in one armature phase in line with circuit *h*, are

$$\frac{2}{3}\, N_h\, \phi_{(0)}\, X_{hm} \qquad \textbf{(1g)}$$

Thus the mutual inductance of circuit *h* and the armature phase is

$$\frac{2/3\; N_h\, \phi_{(0)}\, X_{hm}}{i_{(0)}} \qquad \textbf{(2g)}$$

The linkages in the armature phase due to a normal value of current $I_{h(0)}$ in circuit *h* are, from the definition of normal current in any rotor circuit, simply[34]

$$n\, \phi_{(0)} \qquad \textbf{(3g)}$$

Thus the mutual inductance of the armature phase and circuit *h* is

$$\frac{n\, \phi_{(0)}}{I_{h(0)}} \qquad \textbf{(4g)}$$

But since **(2g)** must be equal to **(4g)** it follows that

$$X_{hm} = \frac{3}{2}\, \frac{n\, i_{(0)}}{N_{h(0)}\, I_{h(0)}} \qquad \textbf{(5g)}$$

or,

$$X_{hm} = \frac{A_{(0)}}{F_{h(0)}} \qquad \textbf{(6g)}$$

where,

$A_{(0)}$ = 2.12 (effective armature times per pole per phase) × (normal r. m. s. armature current).

$F_{h(0)}$ = no-load air-gap ampere-turns of any circuit *h*

In particular,

$$X_m = \frac{A_{(0)}}{F_{(0)}} = \text{per-unit mutual field reactance} \qquad \textbf{(7g)}$$

where,

$F_{(0)}$ = no-load air-gap ampere-turns of field.

Using this relation, it is possible to reduce the calculation of transient reactance to the following items:

A. Determination of synchronous reactance,

B. Determination of the "no-load field currents" of each rotor circuit, *i. e.*, determination of current necessary to give normal fundamental component of armature flux, and

C. Determination of self and mutual coefficients of the rotor circuits between themselves.

## Appendix H

### THE RELATIONS BETWEEN THREE-PHASE AND SINGLE-PHASE REACTANCES

In accordance with the procedure discussed in Part II, the impedances of a machine will be regarded as the ratios of the sinusoidal components of voltage and current due to sinusoidal current in the windings. Since only sinusoidal currents of definite frequency, and only sinusoidal components of terminal voltage of corresponding frequency, are to be considered, it follows that it is legitimate to employ vector notation.

Thus, any current $i = i_0 \sin(t + \alpha)$ will be representable as a vector $\bar{i} = i_0\, \underline{/\alpha}$, and the phase currents will be representable as

$$\begin{aligned} \bar{i}_a &= \bar{i}_1 + \bar{i}_2 + \bar{i}_0 \\ \bar{i}_b &= \bar{i}_1\, \overline{\backslash 120} + \bar{i}_2\, \underline{/120} + \bar{i}_0 \\ \bar{i}_c &= \bar{i}_1\, \underline{/120} + \bar{i}_2\, \overline{\backslash 120} + \bar{i}_0 \end{aligned} \qquad \textbf{(1h)}$$

The phase voltages are similar.

It may be readily verified that with a line-to-line connection between phases *b* and *c*,

$$\bar{i}_1 = -\,\bar{i}_2 = \frac{\bar{i}_{sbc}\, \underline{/90}}{\sqrt{3}} \qquad \textbf{(2h)}$$

where $\bar{i}_{sbc}$ = line-to-line current of phases *b* and *c*, while with a line-to-neutral connection from phase *a* to neutral,

$$\bar{i}_1 = \bar{i}_2 = \bar{i}_0 = \frac{\bar{i}_{sa}}{3} \qquad \textbf{(3h)}$$

where $\bar{i}_{sa}$ = current from phase *a* to neutral.

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[33] The effect of fundamental m. m. f. only is to be considered.

[34] Since only the sinusoidally distributed component of the armature winding is considered, harmonic linkages are neglected.

Under normal conditions of operation, however, it follows from the symmetry of every phase, that the fundamental components of the voltages due to any phase-sequence current distribution must be of the same phase-sequence as the current. Thus, subject to the condition of normal motion of the rotor, there is,

$$\begin{aligned}\bar{e}_1 &= \overline{z_1 i_1}\\ \bar{e}_2 &= \overline{z_2 i_2}\\ \bar{e}_o &= \overline{z_0 i_0}\end{aligned} \tag{4h}$$

but the line-to-line voltage of phases $b$ and $c$ is

$$\begin{aligned}\bar{e}_{bsc} &= \bar{e}_b - \bar{e}_c = 3\,(\bar{e}_1 - \bar{e}_2)\ \diagdown\!\overline{90}\\ &= (\bar{z}_1 + \bar{z}_2)\,\bar{i}_{s\ bc} = \bar{z}_s\,\bar{i}_{s\ bc}\end{aligned} \tag{5h}$$

or line-to-line impedance $= \bar{z}_s = \bar{z}_1 + \bar{z}_2$

Similarly it follows that, subject to the conditions stated, line-to-neutral impedance is

$$z_\sigma = \frac{\bar{z}_1 + \bar{z}_2 + \bar{z}_0}{3} = \frac{\bar{z}_s + \bar{z}_0}{3} \tag{6h}$$

However, these relations do not obtain without special interpretation unless the rotor is moving normally. In case of an "ideal machine" with the rotor stationary, the values of single-phase reactance are given, by the value of $\psi_a - \psi_b$ with $i_a = -i_b = 1$, $i_c = 0$, and $\psi_a$ with $i_a = 1$, $i_b = i_c = 0$, respectively, for a line-to-line or line-to-neutral connection.

Thus, with all rotor circuits closed, the line-to-line static reactance is

$$\begin{aligned}x_s &= x_d'' + x_q'' + \frac{x_d'' - x_q''}{3}\Big[\cos(2\,\theta) - 2\cos(2\,\theta - 120)\\ &\quad + \cos(2\,\theta + 120)\Big]\\ &= (x_d'' + x_q'') + (x_d'' - x_q'')\cos(2\,\theta + 60)\end{aligned} \tag{7h}$$

The value of $x_s$ when the axis of magnetization of the armature coincides with the direct axis of the rotor is

$$x_s = x_{sd} = 2\,x_d'' \tag{8h}$$

When the axis of the armature winding coincides with the quadrature axis the value of $x_s$ is

$$x_s = x_{sq} = 2\,x_q'' \tag{9h}$$

The corresponding line-to-neutral reactances are, with all rotor circuits closed,

$$x_\sigma = \frac{x_0}{3} + \frac{x_d'' + x_q''}{3} + \frac{x_d'' - x_q''}{3}\cos 2\,\theta \tag{10h}$$

When the axis of the armature winding is in line with the poles

$$x_\sigma = x_{\sigma d} = \frac{x_0 + 2\,x_d''}{3} = \frac{x_0 + x_{sd}}{3} \tag{11h}$$

and when the armature axis is in quadrature with the poles

$$x_\sigma = x_{\sigma q} = \frac{x_0 + 2\,x_q''}{3} = \frac{x_0 + x_{sq}}{3} \tag{12h}$$

These relations are useful in determining the values of $x_0$, $x_d''$, and $x_q''$. Thus

$$x_0 = 3\,x_{\sigma d} - x_{sd} = 3\,x_{\sigma q} - x_{sq} \tag{13h}$$

$$x_d'' = \frac{x_{sd}}{2} \tag{14h}$$

$$x_q'' = \frac{x_{sq}}{2} \tag{15h}$$

as mentioned in Part I.

The values of per-unit single-phase reactances which obtain with no closed rotor circuits may also be identified as the per-unit single-phase armature inductances. Thus, in treating the subject of short-circuit currents, Messrs. & Doherty and Nickle[35] employ the relations,

$$\text{line-to-line inductance} = \frac{x_{SD} + x_{SQ}}{2} + \frac{x_{SD} - x_{SQ}}{2}\cos(2\,\theta')$$

line-to-neutral inductance

$$= \frac{x_{\Sigma D} + x_{\Sigma Q}}{2} + \frac{x_{\Sigma D} - x_{\Sigma Q}}{2}\cos(2\,\theta)$$

where, $\theta' = \theta + 30^\circ$

The idea of transient inductance has also been introduced. For example, the transient line-to-line inductance is,

$$\frac{x_{SD}' + x_{SQ}'}{2} + \frac{x_{SD}' - x_{SQ}'}{2}\cos(2\,\theta')$$

In case machines with auxiliary rotor circuits were to be considered, the conception of the subtransient inductance and the use of the double primed notation would also be in order. Thus, for the transient reactances,

$$x_{SD}' = 2\,x_d', \qquad x_{SQ}' = 2\,x_q'$$

$$x_{\Sigma D}' = \frac{x_0 + 2x_d'}{3}, \qquad x_{\Sigma Q}' = \frac{x_0 + 2\,x_q'}{3}$$

and for the sub-transient reactances,

$$x_{SD}'' = 2\,x_d'', \quad \text{etc.}$$

## Appendix I

### NOTATION EMPLOYED

The problem of devising a simple scheme of notation which will be in accord as much as possible with existing nomenclature has not been easy. The difficulty is due to the many terms which pertain to synchronous machines.

The notation of the paper follows the somewhat generally established principle that all armature quantities are denoted by small letters or symbols, and all field terms by large letters or symbols. The subscripts $d$ and $q$ refer to the *direct* and *quadrature* axes of magnetization. The corresponding single-phase line-to-line and line-to-neutral quantities are recognized by the subscripts $s$ and $\sigma$, respectively. Positive phase-sequence terms may be indicated by the subscript 1, but are usually given no special notation. Negative and zero phase-sequence terms are specified by the subscripts 2 and 0, respectively, following the notation introduced by Mr. C. L. Fortescue.[36] All transient quantities are signified by primes.

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[35] Reference (2).

These compose, in the main, the group of indexes required, but various modifications and special designations were necessary. The notation is not peculiar to this paper but is largely the same as the system used by Doherty and Nickle in their recent treatments of synchronous machines. Although it is not urged that this notation be standardized, since the primary purpose has been to fill the requirements of the present article, the system may be helpful to others.

### A. MAJOR QUANTITIES TO BE IDENTIFIED

| | Circuits | |
|---|---|---|
| | Armature | Rotor |
| Voltage | $e$ | $E$ |
| Linkages | $\psi$ | $\Psi$ |
| Current | $i$ | $I$ |
| M. m. f | $A$ | $F$ |
| Reactance | $x$ | $X$ |
| Resistance | $r$ | $R$ |
| Time-constant | $\tau$ | $T$ |
| Flux density | $\beta$ | |
| Time (Electrical radians) | $t$ | $t$ |

Electrical space angle along armature surface with respect to phase "a" $\gamma$

Electrical degrees in direction of normal rotation between axis of poles and magnetic axis of phase "a" $\theta$

### B. USE OF SMALL SUBSCRIPTS IN NOTATION

a. Direct and quadrature quantities.
  direct $d$
  quadrature $q$

These apply to:
  positive phase-sequence armature quantities
  rotor quantities
  single-phase static quantities

b. Distribution.
  1. Armature quantities.
    positive phase-sequence 1, or no subscript
    negative phase-sequence 2
    zero phase-sequence 0
    single-phase line-to-line $s$
    single-phase line-to-neutral $\sigma$
    separate phases $a, b, c$
  2. Rotor quantities.
    direct $d$
    quadrature $q$

Where there are several circuits in any axis they are to be distinguished from each other by numeral subscipts, as $X_{2d}$, except that the symbol, $f$, may be retained for the field winding proper. If no subscript is employed reference to the main field winding is implied.

c. Use of zero as subscript.

Except in connection with time-constants, 0 will indicate zero phase-sequence quantities, and (0) will imply normal, or per-unit quantities.

$T_0$ = field time-constant with all armature phases open.

$\tau_0$ = armature time-constant with all rotor circuits open.

### C. PRIME QUANTITIES

a. With reference to armature reactances:
  sustained—no special indication.
  transient—one prime, *i. e.*, $x'$.
  sub-transient—two primes, *i. e.*, $x''$.

b. With reference to time-constants:
  field time-constant with all armature phases shorted—$T_0'$
  armature time-constants with all rotor circuits closed—$\tau_0'$

### D. ALL SUBSCRIPTS CAPITALIZED

In the present scheme of notation, this form is reserved for the particular single-phase static reactances used by Doherty and Nickle in their paper *Synchronous Machines IV*, and discussed here in Appendix B. These are:

| | |
|---|---|
| total static reactance | $x_D$ |
| static reactance due to space fundamental | $x_{AD}$ |
| static leakage reactance | $x_{LD}$ |
| static transient reactance | $x_D'$ |
| static transient fundamental reactance | $x_{AD}'$ |

As these reactances are single-phase they are also characterized by $S$ and $\Sigma$ to indicate whether they are line-to-line or line-to-neutral, thus

$$x_{SD}, \text{ or } x_{\Sigma D}.$$

Corresponding quadrature values are designated similarly by the subscript $Q$ instead of $D$.

### E. MISCELLANEOUS TERMS

It is necessary to include a number of special terms which have not been discussed above. The notation used for these quantities is more or less arbitrary, but an attempt has been made to employ accepted symbols as much as possible.

$h$ = a subscript denoting any rotor circuit. In conjunction with $d$ or $q$ it signifies that that circuit is in the direct or quadrature axis.

$K_\phi$[37] = a per-unit quantity expressing the ratio of the total flux to the space fundamental component of flux entering the armature along one pole pitch.

$l$ = used as a subscript to denote leakage reactance, or used alone to denote length of armature stacking.

$L$[37] = effective leakage lines per unit length of stacking, linking the entire field winding when the field m. m. f. is one ampere-turn.

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[36] Reference (11).

[37] First employed by Doherty and Shirley in their paper Reactance, reference 10.

$m$ = a subscript denoting mutual reactance between armature and any field winding.

$n$ = a subscript, similar to $h$, denoting any field circuit, or used alone to denote effective armature turns per pole per phase.

$N$ = turns per pole of the main field winding.[38]

$\Delta$ = a coefficient employed to denote increment change in any quantity.

In Appendix E it has been found necessary to devise special notations for certain quantities in order that they fit the construction of the equivalent circuits. These notations employ parentheses and brackets. Their use may be made clear by reference to that appendix.

### PRINCIPAL DERIVED UNIT QUANTITIES

F. The principal derived unit quantities are

$\psi_{(0)}$ = normal armature flux-linkages

$$= \frac{e_{(0)}}{2\,\pi\,f}\,10^8$$

$\phi_{(0)}$ = normal armature flux

$$= \frac{\psi_{(0)}}{n}$$

$\Psi_{(0)}$ = normal flux-linkages of the main field winding $= N\,\phi_{(0)}$

$E_{(0)}$ = per-unit field voltage produced by the variation at normal frequency of normal flux-linkages in the main field $= 2\,\pi\,f\,\Psi_{(0)}\,10^{-8}$

## Appendix J

### PER-UNIT REPRESENTATION OF QUANTITIES

Messrs. Doherty and Nickle, in their recent series of papers on Synchronous Machines, have employed the practise of representing quantities as a decimal fraction of some normal or base value. This method shares with the percentage method of representation, the marked advantage that it eliminates the necessity of employing unwieldy conversion factors in purely analytical work. At the same time, it is definitely superior to the percentage system in that it is unnecessary to continually consider the factor "one hundred." In the percentage system this factor must be specially inserted or divided out whenever the operations of division or multiplication are performed. Therefore, on account of the convenience of the decimal fraction system it will be used hereafter in the paper.

Thus, in the paper, each quantity will have a normal value, and the value of the quantity at any time will be expressed as a decimal fraction of its normal value. For example, normal armature linkages are defined as the linkages which generate normal voltage when varied at normal frequency. Thus, $\psi = 0.45$ means that the armature linkages at the instant of consideration are 45 per cent of this normal value.

Originally, the method of representation used was referred to as "percentage representation of quantities, as a decimal," but this name was to some extent a source of confusion in view of the accepted meaning attached to the word "percentage." Recently the term "per-unit representation of quantities" has been suggested as a designation for the decimal percentage system. As this name appears to solve the difficulties previously encountered, it has been used throughout the paper.

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## Discussion

**A. E. Kennelly:** At the present time, according to the information which has been presented to us, there are possibly thirty-one varieties of reactance in electrical machinery.

It seems important that these useful concepts referred to in these papers as "reactance," "leakage reactance," "differential leakage reactance," and so on, should be clearly set forth and tabulated, because evidently, in the future, when a speaker uses the word "reactance," his audience will want to say, "Which?" It is increasingly important that this matter be thoroughly classified.

The concept which has been presented to us of the per-unit value seems to me of great importance. Percentage, of course, is an expression that we are constantly employing and is very useful, but in computations, percentage is not so convenient, not so simple as per-unitage, and there is no reason why the unit should not have at least as much recognition as the centum, so I hope that method of expression will continue to find favor.

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[38] Effective turns in the case of turbo alternators and induction motors.

**H. H. Spencer:** The papers treat generally of single-phase short circuits and their resulting phenomena, but the trouble which we run into in operating practise is not solely confined to single-phase disturbances. I should like to ask the writers if it is possible simply to superpose the conditions of subsequent short circuits upon the initial equations to determine what may happen later and if so, how the constants here presented must be shaded, and how constants for the three-phase fault can be found.

**S. L. Henderson:** Under the subject of Zero Phase-Sequence Reactance, the statement is made that there is no armature-reaction m. m. f. due to zero phase-sequence currents. This is true for the fundamental current. However, for a third-harmonic current, the currents in the three phases are in time phase, and there is an m. m. f. of three times the number of pairs of poles on the rotor. The effect of this third harmonic m. m. f. can be seen on a delta-connected machine, without $^2/_3$ pitch. The temperature of the field and the losses on short circuit are higher with the machine connected in delta than when connected in star.

I understand, therefore, by the statement in the paper, that there may be an m. m. f., but that there will be no reaction of this m. m. f. on the exciting circuit. Is this because this m. m. f. cancels out in a pair of poles?

**R. H. Park:** Mr. Spencer has inquired how the condition of a three-phase fault occurring shortly after a single-phase fault is to be calculated. A fault of this type may be calculated by determining from the solution for the single-phase short circuit the values of field and armature flux linkages at the instant when the three-phase fault occurs, and then adjusting the a-c. and d-c. components of the three-phase fault to correspond with these calculated initial conditions. Thus, neglecting saturation and extra rotor circuits, the initial value of the a-c. component of the three-phase short-circuit current will be the same as though the three-phase short circuit had occurred at a voltage equal to the product of the voltage before the single-phase short circuit by the decrement of the a-c. component of the single-phase short-circuit current, at the instant at which the three-phase short circuit occurs.

Thus, if the three-phase short circuit begins at time ($t_0$) after the occurrence of the single-phase short circuit the symmetrical component of three-phase short-circuit current will be,

$$i = e\left[\frac{1}{x_d} + \left(\frac{e^{-a f t_0}}{x_d'} - \frac{1}{x_d}\right)\epsilon^{-\frac{t - t_0}{\tau_0'}}\right]$$

If there are several rotor circuits or if it is desired to determine the d-c. component the answer is not as easy. The general method which may be employed is to calculate the effect of impressing, on the open phases of the machine, a voltage equal and opposite to that which would have existed under the condition of single-phase short circuit if the three-phase short circuit had not occurred. If the currents which are found in this way are added to those found from the single-phase short-circuit calculation the sum will be that for the three-phase short circuit.

Mr. Henderson's difficulty in regard to our statement that "there is no armature reaction due to zero-phase-sequence currents" arises from the special interpretation of this term which we have introduced. According to the concept advanced in the paper we would regard as armature reaction only those magnetomotive forces which are stationary with respect to the rotor. The advantage claimed in this view is, that it clearly delineates between those magnetomotive forces which can freely penetrate the rotor, and which do not induce eddy currents in it, and those magnetomotive forces which move relative to the rotor and are thus subject to the demagnetizing action of the currents which they induce. These latter magnetomotive forces are regarded as producing leakage flux.

As stated in the paper the exact line of demarcation between armature reaction and armature reactance must necessarily be drawn arbitrarily. It is hoped, however, that the distinction made will prove to be a useful one.

As to the possibility of the reaction of the third-harmonic m. m. f. due to zero-phase-sequence current on the exciting circuit, it is of course understood that m. m. f's need not be considered as directly reacting on each other, but that we are entitled to find the effect of two m. m. f.'s by adding the effects that would be due to each acting separately. Now in general the d-c. current in the field will produce an armature voltage of fundamental and all harmonic frequencies. A third-harmonic zero-phase-sequence current will develop armature m. m. f. of third and multiples of third harmonic frequency in space, varying in time at three times normal frequency. To the extent that the reluctance of the air gap is not uniform these m. m. f.'s can give rise to fluxes of frequency in space different from their own, and it is to just this extent that they can give rise to other than third-harmonic armature voltage. Since the third-harmonic m. m. f. in question is pulsating at three times normal frequency, half of it may be regarded as moving forward at synchronous speed, thus stationary with respect to the poles. In the case of a salient-pole machine this third-harmonic m. m. f., stationary over the poles, can give rise to a fundamental component of flux, also stationary over the poles, and thus generating voltage of normal frequency in the armature. Ordinarily, however, this effect is very small. Were it present in a delta-connected machine, not of $^2/_3$ pitch, a slight change (increase or decrease) in the fundamental component of voltage would be expected when the delta is opened or closed.

The fact that the third-harmonic circulating current of a delta-connected machine, not of $^2/_3$ pitch can cause very appreciable losses makes it desirable that a means of calculating these currents be available. If the third-harmonic voltage of the open delta is first calculated, the current that will result when the delta is closed can be found by dividing this voltage by three times the third-harmonic zero-phase-sequence reactance, which in turn will, in general, be slightly more than three times the corresponding fundamental zero-phase-sequence reactance. The reason that the third-harmonic zero-phase-sequence reactance is slightly greater than three times the corresponding fundamental value is that, as mentioned above, in the case of third-harmonic current, half of the space third-harmonic m. m. f. is stationary with respect to the poles, and thus is not subject to the demagnetizing action of the rotor. Usually this effect is not very great. It can, however, be corrected for by modifying the value of ($K_0$) in Mr. Alger's formula for zero-phase-sequence reactance.

# The Thermal Volume Meter

BY G. W. PENNEY[1] and C. J. FECHHEIMER[1]
Associate, A. I. E. E. Fellow, A. I. E. E.

***Synopsis.***—*The thermal volume meter was originally brought out by Professor Thomas, and is frequently called a Thomas meter. The principle is that the temperature of the gas is raised by means of an electrical heater, the change in temperature being accurately measured either by means of resistance thermometers connected in a wheatstone bridge network, or by means of a thermopile. It is believed that the thermocouple method is preferable to resistance thermometers, and most of the paper deals with that construction.*

*The usual construction has walls of wood or micarta, which serve as an insulating support for the heater coils and thermocouples. The general proportions of the volume meter as to section and length are dealt with, the former being determined mainly by the mean velocity of the air, and the latter by the distance needed to give the gas an opportunity to mix after passing the heater. A sufficient number of thermocouples is required to give a good reading of the potentiometer with a comparatively low temperature rise of the gas and also to obtain a good average of the gas temperature. The details of construction are described. The equations that are suitable for calculating the volumes of the gas are then given.*

*Then follows considerable discussion on the possible sources of error in the meter, the principal ones being*

*The non-uniform heating of the gas.*
*Non-uniform distribution of velocities.*
*Heat escapement.*

*Methods are suggested for determining the magnitude of these various conditions experimentally or by calculation. There are several minor sources of error, such as:*

*Time lag of meter.*
*Unsteady source of e. m. f.*
*Instrument errors.*
*Heat flow along thermocouple wires.*
*Loss of pressure in passing through the meter.*
*Variation of specific heat and humidity.*

*Most of these are shown to be of negligible effect.*

*Some notes on design which include means of calculating the proportions of the heater are given.*

*In Appendix I the advantages and disadvantages of the various methods of measuring gas volumes are included. In Appendix II will be found some notes on comparison of resistance thermometers and thermocouples for temperature measurement. In Appendix III consideration is given to the electrical machine as a thermal volume meter.*

## INTRODUCTION

THERE are many ways of measuring the volume of flow of gases, each having advantages and disadvantages. The most important of these methods are given in Appendix I, together with reasons why they are not generally well adapted for the measurement of air volumes passing through electrical machinery. With most of the more accurate methods the principal objection is that the pressure drop is so great as to reduce the volume considerably (*e. g.*, the orifice method). In the thermal volume meter, this objection is met by using a short duct in which the velocities are only moderate and the obstructions very small, so that the resistance to flow is very slight.

The thermal volume meter was first brought out by Prof. Carl Thomas, and is frequently called a Thomas meter.

The principle of operation of the instrument is that the temperature of the gas is raised, the temperature increase and amount of heat required to produce that change in temperature being accurately measured. As the specific heat at constant pressure has been accurately determined, the mass of the gas flowing per unit of time can readily be calculated. As most engineers are more interested in the volume than in the mass, the change to volume can easily be made if one has a knowledge of the absolute pressure and temperature. In practise, the gas is heated electrically. The temperature increase is measured by one of two methods: (1) by means of resistance thermometers placed before and after the heater, they being used as two arms of a wheatstone bridge; and (2) by means of thermocouples connected in series (frequently called a thermopile). A comparison of these two methods of temperature rise measurements is given subsequently. It is believed that the latter method using thermocouples is preferable, and the following description pertains to that type.

In this paper are given the experiences of the writers and their co-workers at the Westinghouse Elec. & Mfg. Company; there is very little in the technical literature on the subject with which to make comparison.

Some of the data in this paper have appeared elsewhere, but as they were scattered, it was thought best to combine them with those which have not been previously published.

## CONSTRUCTION OF THE THERMAL VOLUME METER

As electrical conductors are used for the heater and for the thermocouples, it simplifies the construction to use for the walls material that is an electrical insulator. That has an additional advantage, as an electrical insulator is usually a poor heat conductor, and to secure accuracy it is essential that escape of heat from the outside be avoided. In all but the smallest sizes, pine or maple wood has been used; and for the smaller sizes, such as is shown in Fig. 1, micarta plate was the material adopted. The walls are then thermally "insulated" with cork board. In the larger sizes with wooden walls about 1 in. thick, and with internal temperatures of the air not over 5 deg. cent. above atmospheric temperature, it was found that the heat loss from the outside was negligible, even though

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[1] Both of the Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., February 13-17, 1928.*

there was no heat insulating material added to the exterior. This heat loss can be calculated close enough to determine whether or not insulating material should be added, and how much.

In Fig. 1 is shown a small meter with one side removed for inspection. The inside dimensions are 3½ by 3½ by 18 in. It is suited for handling from about 60 to 300 cu. ft. per min. This meter had micarta walls, fastened together with machine screws. In Fig. 2 is shown a medium size volume meter in which the sides are made of planed pine lumber about one in. thick.[2]

It has been found desirable to wind the heater element on a mandrel with the wires close together, and then stretch them like a spiral spring. These are arranged in a number of coils of equal numbers of turns, and are supported by means of screw-eyes in the walls. This scheme of construction for the heater coils is shown in Fig. 1. It is desirable to keep the axes of the spirals vertical; otherwise, with the axes horizontal, when the coils heat the wires may sag and there is then the possibility of part of a coil short circuiting on another coil. In the larger volume meters it is desirable to support the heater coils say half way, or one-third and two-thirds the way up, for which glass rods have been found to be suitable. In Fig. 1 four rows of heater coils were used; in all but the very small meters, two rows of heaters are sufficient, and these are then staggered with respect to each other.

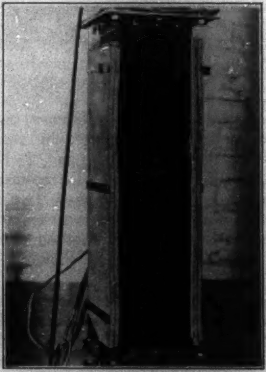

FIG. 1—A SMALL VOLUME METER WITH ONE SIDE REMOVED FOR INSPECTION

The distance between the heater coils and the thermocouple junctions is largely a matter of how far the gas must flow to mix fairly well; it has been the practise of the writers to make that distance at least as great as the mean of the two cross-sectional dimensions for the large meters, and about two to three times as great for the smaller meters. It would be of interest to learn from others what their practise has been.

It is desirable to use small screw-eyes in order that the heater wires may be close to the walls, thereby securing as uniform distribution of heat as possible throughout the cross-sectional area.

The number of thermocouples used has never been less than 16, and usually the number is more. With a large number of thermocouples a good average of the temperature increase of the air is obtained and a fairly high reading of the potentiometer is secured. Thus, with 40 microvolts per degree per couple, and with 25 couples, a reading of 2 millivolts is obtained with only 2 deg. cent., increase in air temperature. In arranging the locations of the thermocouple junctions, the rectangular area is broken into as many equal squares as there are thermocouples, and a junction is placed in each square. The scheme of arrangement for 25 thermocouples all in one plane, in a square duct, is indicated in Fig. 2. In the small volume meter shown in Fig. 1, for simplicity of construction, each set of thermocouple junctions is arranged in four planes. It is well to select the wires of such size that, with the arrangement adopted, the flow of heat along the wire to wall will not be sufficient to alter appreciably the temperature of the junction. The thermocouple wires within the meter are all bare. The scheme of connections is shown in Fig. 3, where for simplicity two thermo-

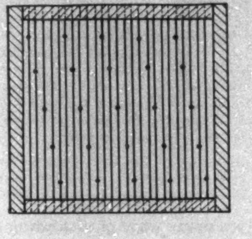

FIG. 2—CROSS-SECTION SHOWING LOCATION OF THERMOCOUPLE JUNCTIONS

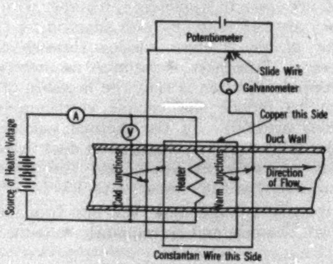

FIG. 3—WIRING DIAGRAM OF A VOLUME METER

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[2] See paper by Laffoon and Calvert: *Additional Losses of Synchronous Machines*, TRANS. A. I. E. E., Vol. XLVI, 1927, p. 84.

couples are shown. The junctions are usually made by slightly overlapping the wires, and silver soldering; or, in the larger meters, they may be made by twisting the wires and soft soldering. It is interesting to note that all wires on one side of the meter are of one kind of metal, say constantan, and opposite another kind such as copper. Thus, only copper wires are brought to the potentiometer. It has been found simplest, in making the required number of junctions, to bring out the leads through suitably drilled holes in the walls of the meter and make the connections on the outside. These may be simply twisted, preferably soldered.

It is important that the thermocouples placed in the cool stream be at the same distance from the heater as those in the warmed gas. Otherwise, heat radiation will play its part unequally, thereby introducing a large error, even when the heater coils are at a comparatively low temperature.

In dry weather, static electricity has been known to affect the reading of the potentiometer, and it is well, therefore, to ground one of the thermopile leads.

### EQUATIONS FOR COMPUTING VOLUMES

It may readily be shown that

$$Q = \frac{0.03155}{\gamma C_p} \frac{W}{\theta} \qquad (1)$$

Here $Q$ = cu. ft. per min. of the gas.
$\gamma$ = density in lb. per cu. ft.
$C_p$ = specific heat at constant pressure.
$W$ = watts absorbed by the gas.
$\theta$ = temperature rise of the gas.

For dry air, the density at 25 deg. cent. and 29.92 in. of mercury may be taken as 0.074, and the specific heat as 0.2418. Then for such conditions,

$$Q = 1.765 \frac{W}{\theta} \qquad (2)$$

For any other than standard conditions, the law of a perfect gas may be used, so that then

$$Q = 1.765 \left( \frac{273 + t}{273 + 25} \right) \frac{29.92}{P} \frac{W}{\theta}$$

$$= 0.177 \left( \frac{273 + t}{P} \right) \frac{W}{\theta} \qquad (3)$$

Here $t$ is the temperature of the air, deg. cent., and $P$ is the total pressure in in. of mercury.[3] The influence of humidity is so small that it may well be neglected. The order of error is discussed under "Sources of Error."

In the volume meter, there are $n$ thermocouples for each of which there are $E$ microvolts per deg., the reading on the potentiometer being $e$ millivolts. Then

$$\theta = 1000 \frac{e}{n E} \qquad (4)$$

which substituted in equation (3) gives:

$$Q = \frac{0.177\, n E W}{1000\, e} \left( \frac{273 + t}{P} \right) \text{ cu. ft. per min. for air} \qquad (5)$$

$$\text{or } Q = \frac{0.03155\, n E W}{\gamma C_p e} \text{ cu. ft. per min. for any gas} \qquad (6)$$

$Q$ = cu. ft. per min.
$E$ . = microvolts per deg. from calibration curve.
$W$ = watts input to heater (absorbed by the gas).
$\gamma$ = density of gas in lb. per cu. ft.
$C_p$ = specific heat of gas at constant pressure (about 0.2418 for air).
$e$ = millivolts as read on potentiometer.
$t$ = gas temperature in volume meter, deg. cent.
$P$ = absolute pressure in in. of mercury.

The calibration curve of the thermocouples is nearly, but not quite, a straight line. In general, its equation may be written as:

$$V = a t + b t^2 + c t^3 \qquad (7)$$

where $V$ is the millivoltage, $t$ the temperature, and $a$, $b$, and $c$ constants.

For most cases the third term may be dropped. The microvolts per deg., $E$, will then be:

$$E = 10^3 \frac{dV}{dt} = 1000\,(a + 2\,b\,t) \qquad (8)$$

Equation (8) is that of a straight line which may be plotted; or a chart may be used combining the constant and the terms $(273 + t)$ and $P$ from equation (5) with $E$.

It is important to secure an accurate calibration curve, and if there are not facilities available, a sample of the wire may be sent to any of the well-recognized laboratories, such as the Bureau of Standards, where a very accurate calibration can be obtained. One of the manufacturers of constantan wire has a standard calibration, and it keeps its products so close to that curve that it is usually sufficiently accurate to accept its data without further checking.

### POSSIBLE SOURCES OF ERROR

The principal sources of error are non-uniform heating of the gas; non-uniform distribution of the gas; and heat escapement.

*Non-uniform Heating of the Gas* has been previously mentioned. To discuss this, it is assumed that the velocities are uniform throughout the section. It is manifestly impossible to secure uniform distribution of loss in the heater coils, for to secure that would mean that the heater covered the entire section. By making the volume meter fairly long the gas has more of a chance to mix after it has passed the heater. It is believed that the heater coils tend to produce some turbulence in the gas stream, which assists in mixing the gas. Then by employing a large number of thermocouples the error becomes practically negligible. In some of the tests the e. m. f. per thermocouple was measured, which was easily done by removing the insulation from the joints of the series connections on one side of the meter, using a sensitive potentiometer and galvanometer for balancing. It was usually found that there was considerable variation in e. m. f. per couple, but with a large number of couples, the average of the readings was so close to the true average that the error was very small. For example, the volume meter with 20 thermocouples, shown in Fig. 1, was checked against a converging nozzle, designed in accordance with data in the paper by Dr. S. A. Moss.[4] In three sets of readings, in which the air was heated 3 deg. to 6.8 deg., the difference between the nozzle and volume meter readings were + 0.4, − 0.8, and − 1.5 per cent, the plus sign meaning that the volume meter read high. Yet readings of individual thermocouples varied from 0.40 to 1.05 millivolts, with an average of 0.827 millivolts, thus showing 51.5 per cent below, and 27 per cent above, the mean. In this case the velocity distribution was very good, the error due thereto being probably less than 0.3 per cent.

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[3] It will readily be seen that the volume per unit time changes with the density as the gas passes through the apparatus. The particular value of $t$ and $P$ to be used in equation (3) are those corresponding to the location where the value of volume is desired: this might be ahead of, behind, or within the meter. In most cases, the differences in density at various locations are so small as to be negligible.

*Non-Uniform Distribution of the Gas.* In the above, where non-uniform heating was considered, it was assumed that the velocities were uniform throughout the meter. In general, that condition cannot be obtained but can be approached close enough to reduce the error, due thereto, to negligible magnitude. The effect of non-uniform velocities is different from non-uniform heating. Thus assuming uniform heat distribution, the temperature increase of the gas as it passes through the heater coil is nearly inversely as the velocity. On the other hand, if the velocities are uniform, the temperature increase is directly proportional to the heat per unit of area. It is because of the reciprocal relation with velocities that great departures from uniformity should be corrected. In a number of the earlier tests it was found that the air in some small areas actually moved in the reverse directions to the main air streams. Then the cool and warm thermocouple junctions were reversed, and a very large error was introduced. It is not essential that the velocities be uniform, but the departures should not cause the errors in measurement to be more than about one per cent. Then there may be considerably greater irregularities than for, say, pitot tube measurements.

If the sectional area of the duct be broken into a number of small but equal areas, through any one of which the velocity be considered as uniform and be assumed to obtain throughout the length of the volume meter, then the ratio of the volume that would be measured were the velocities uniform to the volume that is measured given by:[5]

$$R = \frac{(\Sigma V)\left(\Sigma \frac{1}{V}\right)}{n^2} \qquad (9)$$

Here $V$ is the velocity in the small section, and $n$ is their number, that is, multiply the volume as measured by $R$ to obtain the correct volume.

To determine the velocity distribution an impact tube has been used. In some cases the air discharges from the meter directly to the atmosphere so that the impact tube can be used conveniently; although in some cases the duct just beyond the meter must be removed. A suitable impact tube may then be used without considering the differential pressure, as the surrounding pressure is atmospheric, the same as on the open side of the manometer. The section may conveniently be divided into a suitable number of equal squares by means of small wires drawn taut, and the impact tube placed in turn at the approximate center of each square. A suitable, rigid support should be provided far enough back from the issuing stream so as not to interfere with streams before they issue.

In some cases the duct system beyond the volume meter cannot readily be removed, and then slots can be cut in the duct preferably before and after the meter. As used by the authors, the explorations were made in horizontal and vertical directions, (with the flow horizontal), but only along the center lines. The static pressure was usually fairly high, and the differential pressure was then read using an ordinary pilot tube which was passed through the slot. It was necessary to hold the tube rigidly, suitable clamping being provided and tightened for every setting of the tube.

While uniformity of velocities is not essential it has been our practise to make the velocities sufficiently alike to reduce the error to about one per cent, or less, as given by equation (**9**). When the air is to be taken directly into the volume meter from the atmosphere, the *vena contacta* arising from sharp entrance conditions should be avoided and a suitably curved, converging intake should be provided such as is shown in Fig . 4. It is often convenient to provide a curved, converging intake when the volume meter is made part of a duct system. This scheme was shown in Figs. 3 and 6 in a previous paper.[6] There are times when there is liklihood of having poor distribution of velocities, and when a converging duct cannot conveniently be used. Then, suitable "air straighteners" in a duct ahead of the volume meter have been employed. These consist of about three vertical and three horizontal planes of sheet metal (assuming the air flow to be horizontal). These planes are hinged at one end and the other end can be moved externally by means of suitable rods, or the like, which can be clamped in any position.[7] Adjustments are made until the distribution is satisfactory.

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[4] "The Impact Tube," American Society of Mech. Eng. 1916.

[5] *The derivation of this equation is given in the Appendix of paper, "Performance of Centrifugal Fans for Electrical Machinery," A. S. M. E., 1924.

[6] *Ventilation of Turbo Alternators; Concluding Study*, A. I. E. E. Trans., Vol. 45, pp. 255, 256.

It should be especially noted that an obstruction within or just ahead of the meter, or a sudden bend, etc., which may tend to produce poor velocity distribution, should be avoided. On the other hand, if there is a fairly long, straight duct ahead of the volume meter the velocity distribution will probably be sufficiently satisfactory. Generally, the distribution just after the air leaves the volute around a centrifugal fan is not of enough uniformity.

*Heat Escapement.* To secure accurate measurements all of the heat generated in the heating coils must be absorbed by the gas passing through the meter, and the heat loss from the walls must be of no consequence.

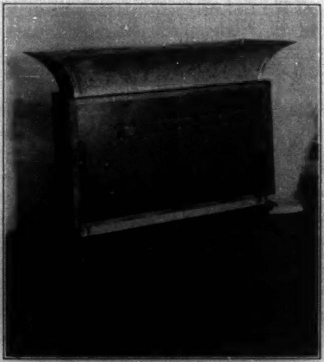

FIG. 4—MEDIUM SIZED VOLUME METER

In the earlier calculations tests in which moderate size volume meters with wooden walls were used, and the difference between the internal and external temperatures were generally less than 4 deg. cent., the losses of heat from the outside surface, were negligible. But in later tests, when small volumes were to be measured with perimeters that were large in relation to the cross-sectional areas and with their walls of higher thermal-conducting material, the heat loss was sufficient to introduce an appreciable error. The air entered the meter not far from the discharge of a centrifugal fan, which was operated at low volumes, high pressures, and inefficiently. The temperature of the air entering the volume meter was consequently serveral deg. cent above the temperature of the surrounding atmosphere. By adding several layers of corkboard to the outside, the heat loss was made practically negligible. Another way of remedying the difficulty is to surround the meter with a jacket of air at about the same temperature as the air inside, which in this particular case could have been done by letting a little of the air, as discharged from the fan, go through the jacket and then escape to the atmosphere. If the meter is measuring the air discharged from an electrical machine, the air entering the meter may be considerably warmer than the surrounding air, which in some cases may give a correspondingly large heat dissipation in passing through the meter. A test for this error is to pass the initially heated air through the volume meter with no current in the heater coils and measure the decrease in temperature using the thermocouples and potentiometer. If a temperature change can be detected there is an error due to heat dissipation.

It is believed to be desirable to maintain fairly low temperatures of the heater, the design being such that it is of the order of 50 deg. cent. above the air. With high heater temperatures, there will be appreciable transfer of heat by radiation to the walls, and thence by conduction through the walls to the outside air. Such loss of heat, which cannot be recorded by the temperature-measuring device may introduce a considerable error.

Although the heater temperature is only about 50 deg. cent. above the air, the watts per sq. in. of wire surface are generally considerably higher than for, say, insulated conductors in an air stream, or bare conductors in still air. The reasons are that the wires are of small diameter; are bare; and are right in the air stream. In one instance the mistake of bringing one of the heater wires as a lead through the wooden wall, was made and the wood was burned by the high temperature that the wire attained. There was a small error introduced because some of the heat generated in the wire buried in the wood was not taken up by the air passing through the volume meter. It has been found satisfactory to place a short loop of the wire under a small brass bolt head or washer, the bolt being used as a terminal. There may then still be a small error due to very small heat escapement through the bolt, but that is generally negligible.

### MINOR SOURCES OF ERROR

*Time Lag of Meter.* As in any thermal device, time is required to reach a steady state of temperature. That

$$\text{time constant}^8 \text{ is practically } \frac{\text{rate of storage heat}}{\text{rate of dissipation of heat}}.$$

Unlike many other thermal devices, the time constant seems to be greater the smaller the meter. In the larger thermal volume meters, the potentiometer connected to the thermocouples may be read in considerably less than a minute after the current value is fixed. In some cases, it seemed unnecessary to wait at all after the value of heater current was fixed. But in some tests made with a small volume meter (1½ in. square in section) it was sometimes necessary to wait more than ten min. until the potentiometer reached a steady value. Fig 5 shows time-temperature curves for a small volume meter. The temperature as indicated by the thermocouples is plotted as a function of the time in minutes after closing the heater switch. This is done for a normal rate of air flow through the meter, and also for a low rate of flow, and shows that the sluggishness increases as the volume decreass. The percentage of error as derived from the temperature curves is also plotted against the time. The sensitivity of the meter was indicated by a sharp break in a cooling curve when a door leading out of the building was opened in cool weather. These latter data are not given in this paper.

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[7] This scheme is shown in Fig. 1 in paper, "Performance of Centrifugal Fans for Electrical Machinery, A. S. M. E., 1924. See also text following "The Test Rig."

[8] This refers to the time constant in the usual exponential equation.

*Unsteady Source of E. m. f.* From the above it will be seen that it is important to have a steady source of e. m. f. for the heater, particularly when there is liable to be a considerable time lag. Often, to simplify tests, the heater is connected through a rheostat to a fluctuating shop circuit, and then it is found nearly impossible to duplicate one's readings.

*Instruments.* If suitably checked, and direct current is used, ordinary indicating ammeters and voltmeters are suitable for measuring the power input to the heater. If the heater material be of negligible temperature coefficient, dividing the volts by the amperes should give a constant, an additional check on the readings. If alternating current is used, an accurate watt-meter may be employed, or usual ammeter and voltmeter if it is found that the circuit is non-inductive. Very sensitive potentiometers are obtainable for measuring the thermocouple e. m. f. However, most of the galvanometers used for balancing are not sufficiently sensitive. Recently a small portable reflecting galvanometer has been used, and the sensitivity has been much improved.

*The Thermocouples.* As previously pointed out, the walls, plus heat insulation, if used, should limit the flow of heat through them to a negligible quantity. This should imply that the inner wall surface temperature equals that of the air stream adjacent to it. A short distance from the inner-wall surface the air temperature may be slightly different from that right at the wall, and a thermocouple junction may be placed there. If the thermocouple wire is large enough heat may flow from the junction to the wall to affect the temperature at the junction. Therefore, it is desirable to select wire that is just large enough to possess the necessary mechanical strength, and yet prevent enough heat-flow longitudinally to affect the junction temperatures. To secure an accurate average of temperature some junctions must be near the walls, following the arrangement indicated in Fig. 2. It is also evident that to read the correct temperature a little farther away from the wall, where the air temperature is higher, by thermocouple, the cooler air stream near the wall should not affect the junction temperature.

As previously stated, there may be a very considerable error if the cold and warm thermocouples are not symmetrically placed with respect to the heater, (due to unequal radiation), even if the heater is worked at a comparatively low temperature.

In taking observations it is usually well to take at least two sets of readings with different watts input to the heater, for the same volume. The watts divided by the millivolts should not differ more than about one per cent. This is a means of checking unequal radiation to the cold and warm junctions.

*Effects of a Drop in Pressure in Passing Through the Meter.* When using a volume meter for measuring a much larger volume of air than normal, there may be a considerable pressure drop in the meter. Since this represents a dissipation of potential energy it may be thought that this may result in an increase in air temperature with a corresponding error in the indicated volume. Taking an extreme case, if the energy dissipated went to increase the temperature of the air, a pressure drop of one in. of water would give an increase in temperature of 0.21 deg. cent., which would be a serious error when as ordinarily used the rise in the volume meter is only two to four deg. cent. However, the expansion of the gas tends to cool it and the energy dissipated tends to heat it, so that these two effects compensate for each other. Or, stated differently,

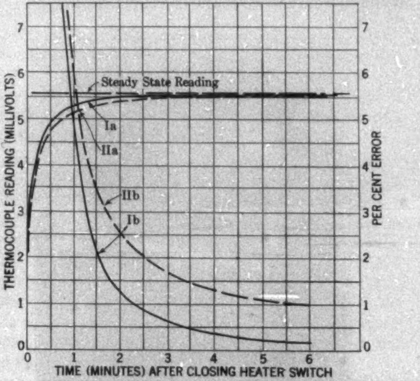

FIG. 5—TIME-TEMPERATURE CURVES FOR A SMALL VOLUME METER

Ia. Thermocouple reading in millivolts plotted against time in min. after closing the heater switch, with a normal rate of air-flow through the meter.

IIa. Same as Ia except a low rate of air-flow through the meter.

Ib. Per cent error plotted against time at which the temperature is read for normal rate of air-flow through the meter.

IIb. Same as Ib except a low rate of air-flow through the meter.

when gas is expanded by a throttling process the total energy content of the gas is unchanged so that for a perfect gas there would be no change in the temperature. In actual gases there may be some very slight change in temperature which may either heat or cool the gas depending on the initial temperature and pressure; but under conditions prevailing in the thermal volume meter, they are negligible.

*Influence of Variation in Specific Heat and Humidity.* Errors introduced by neglecting the influence of change of specific heat with temperature, and of various percentages of humidity are very small, and it is believed that for practically all engineering work, their effects upon volume meter readings may be ignored. According to Mark's Mechanical Engineers Hand Book, the specific heat of dry air at 10 deg. cent is 0.2412, and at 50 deg. cent. it is 0.2422,—a difference of only 0.41 per cent, over a probable greater range of temperatures than will usually be encountered.

As to humidity, the density decreases and the specific heat increases the greater the humidity, the product of the two changing very little. At 25 deg. cent and 29.92 in. of mercury, for dry air the product is 0.07403 by 0.2418 = 0.0179. For 100 per cent moisture it is 0.07317 by 0.2462 = 0.01801. The difference between these two products is only 0.6 per cent, and this is for greater extremes than will be found in test.

### SOME NOTES ON DESIGN

Let $W$ = watts input to heater.
$d$ = diameter of wire in heater, in.
$l$ = length of wire in heater, in.
$\rho$ = resistivity of metal used in heater in ohms per square in. per in.
$S$ = surface of wire in heater, sq. in.
$V$ = mean velocity of gas, thousands of ft. per min.
$E$ = E. m. f. across heater.
$\theta$ = temperature rise of wire above air.

Then

$$W = \frac{\frac{\pi}{4} d^2 E^2}{\rho\, l} \qquad (\mathbf{10})$$

$$S = \pi\, d\, l \qquad (\mathbf{11})$$

The formula that has been used for the rate that heat is transferred from the wire to the air is:[9]

$$\frac{W}{S\,\theta} = \frac{\left(\frac{1.21}{d} + 595\right)\sqrt{1 + 20.3\,V}}{10^4} \qquad (\mathbf{12})$$

The first term in the numerator may be dropped without much error, and the three equations may then be combined and solved:

$$l = 2.82 \sqrt[3]{\frac{W}{\rho\,(1 + 20.3\,V)} \left(\frac{E}{\theta}\right)^2} \qquad (\mathbf{13})$$

$$d = 1.13 \sqrt{\rho\, l\, W} \qquad (\mathbf{14})$$

from which the length and diameter of wire may readily be calculated. When these are determined, the arrangement of the various parts may be determined by means suggested in other parts of the paper. The watts loss is determined from a knowledge of the approximate volume of air and the temperature rise of the air.

Velocities of air from about 400 to 4000 ft. per min. have been used in volume meters. When using the above equations, one should estimate on the highest velocity anticipated, as, for a given temperature rise of the gas, the higher the velocity the higher the temperature of the heater coils.

## Appendix I

### ADVANTAGES AND DISADVANTAGES OF VARIOUS METHODS OF MEASURING GAS VOLUMES

The measurement of air volumes is very difficult because air cannot be weighed by the methods ordinarily used for weighing or measuring solids or liquids, nor does its flow follow simple laws such as for the flow of an electric current. For these reasons, rather indirect methods must be used for measuring air volumes. There are many different methods, and each has advantages which make it applicable to certain cases. The following are some of the most commonly used methods:

1. Direct measurement of total volume by means of a gas-holder or gasometer.
2. Measurement by displacement of volume per unit of time (*e. g.*, an ordinary gas meter).
3. Measurement by means of an anemometer of the velocities of the air passing a given area.
4. Measurement of the pressure drop across a given orifice.
5. Measurement of the velocity of discharge from a nozzle, using an impact tube to measure the velocity head.
6. Measurement of velocities in a duct by means of a pitot tube.
7. Measurement of pressure change in a converging (subsequently diverging) channel, known as a Venturi tube.
8. Measurement of volume per unit of time by means of a thermal volume meter.

A few of the advantages and disadvantages of these eight methods are given below, in brief:

1. The gasometer is the absolute method for accuracy. Its very large size prohibits its use except for calibrating other devices, and then only for the smaller rates of flow. For example, the air from a 10-hp. motor, if caught for one minute, would probably occupy about 100 cu. ft.

2. The ordinary gas meter is also too large, except for small volumes of flow. Also, in most displacement meters the pressure drop is prohibitively high for use

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[9] Taken from paper by Kennelly, Wright and Van Bylevelt, TRANS. A. I. E. E., 1909, p. 388.

with electrical machines. It is an accurate means of measurement.

3. With an ordinary rotating-vane anemometer, it is usually found very difficult to get accurate results. The instrument itself is liable to disturb the flow; the resistance that it offers to the flow may reduce the volume of air through that part of the section in which the instrument is placed. If held by hand, the arm and hand disturb the flow and seriously affect the reading. The anemometer is a delicate instrument, and its calibration is liable to change. It may be used with a fair degree of accuracy when the total volume of air passes through it,[10] but that is necessarily a limited application. So far, the hot-wire anemometer has not been successful, as it is usually too sensitive for direction of flow.

4. The measurement of pressure drop across an orifice is very satisfactory where the pressure drop necessary to obtain a reading of reasonable magnitude is not objectionable. The orifice requires calibration, but fairly complete published data are available giving the calibrations.[11] A considerable length of straight duct is required, both ahead of, and past the orifice, as otherwise the measured pressure drop across the orifice may be changed. For these reasons an orifice is seldom, if ever, used for electrical machines. The method has been used successfully in work on models, but even then the applications were rather special.

5. When a pressure drop of the order of an inch of water is permissible, the air may be discharged through a nozzle or stack, and the velocity head of the stream may be measured by means of an impact tube and an ordinary manometer. Some rather extensive data are contained in a paper by Dr. S. A. Moss,[4] but as the conditions may be different in the electrical machine, it may be advisable to do some experimental work to find a form of nozzle which will give approximately uniform discharge velocities. An example of a stack is shown in Fig. 2 in a recent paper by Laffoon and Calvert.[12] The stack is applied to a turbo alternator, and in many such high speed machines the volume is affected but little by the additional pressure needed for the stack; and if the fan characteristic is approximately known the volume can readily be corrected so as to allow for the reduction.

6. With a pitot tube, it is essential to have a long straight duct so as to eliminate most of the eddies, and the velocities must be high enough to secure high enough reading to insure reasonable accuracy. The long straight duct is usually very inconvenient, and there may be an appreciable pressure drop due to the length of the duct, fairly high velocity and losses at the bend usually essential at the ends of the duct. Even so, unless the pitot tube is used with considerable care, errors will be introduced. For these reasons this method is seldom applicable to electrical machines.

7. The Venturi tube is used frequently with liquids, but seldom with gases. The authors have not had practical experience with this device, but it appears that unless the converging channel is made carefully, and the taps for pressure drop placed with precision, the meter is not accurate. Venturi meters were used in some tests a few years ago with apparently considerable success.[13] There will be some loss of pressure, as, with the divergent channel following the convergent duct, some head must be lost. It is believed not to be in general suitable for use with electrical machinery.

8. One of the principal advantages of the thermal volume meter is that the pressure drop through it is very small, as the obstructions offered by the heater coils and the temperature-measuring devices are not of great magnitude. Furthermore, the velocity can be low as compared with that needed with most of the other methods enumerated above, which also means low pressure drop.

## Appendix II

### SOME NOTES ON COMPARISON OF RESISTANCE THERMOMETERS AND THERMOCOUPLES FOR TEMPERATURE MEASUREMENT

In some of the earlier work of one of the writers, (about ten years ago), resistance coils were used, consisting of fine copper wires stretched zigzag across the air passage, the wires in the cold and heated air forming two arms of a wheatstone bridge, the other two arms being of constant resistance external to the volume meter. No connections were changed once the circuit was formed, so that there could be no error introduced due to a change in contact resistance. The network was so arranged that with a predetermined temperature rise of the air the galvanometer read zero. The loss in the heater was altered until this condition was obtained. However, this way of operating is very slow and tedious because there is a time lag between a change of the heat input and the resulting change in resistance. This makes it very difficult to secure a balance if there are fluctuations in voltage or air flow. A much more convenient method is to adjust the heater current to a given value and read the resulting temperature rise of the air, but this requires changing the contacts when measuring resistance.

An inherent difficulty in using resistance coils is that the rise in temperature is small, so that the change in resistance is very slight and, therefore, extreme accuracy is required in measuring the resistance. Thus, for two deg. cent. change in air temperature the change in resistance is only 0.8 per cent; consequently the maximum allowable error in measuring this resistance is about 0.008 per cent for one per cent error in volume.

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[10] An instance of this was described in paper *An Experimental Study of Ventilation of Turbo Alternators*, A. I. E. E. TRANS., Vol. 43, 1924, p. 480.

[11] J. M. Spitzglass, "Orifice Coefficients, Data and Results of Tests, *Trans. of A. S. M. E.*, 1922. Also report of A. S. M. E. Special Committee on Fluid Meters, Part I, 1924.

[12] *Additional Losses of Synchronous Machines*, TRANS. A. I. E. E., Vol. XLVI, 1927, p. 84.

[13] "The Operation of Blowers in Parallel for Forced Draft in Naval Service," M. C. Stuart, *Jl. of Amer. Soc. for Naval Engrs.*, Nov. 1920.

Even though resistance can be measured with great accuracy with a wheatstone bridge network, it is believed that such order of precision is too much to expect. On the other hand, each thermocouple measures the temperature rise of the air between the two points in the cool and warm air where the two junctions are located. A given percentage error in measuring the e. m. f. of the thermocouple produces the same percentage error in the air volume. But when using resistance thermometers a given percentage error in measurement of resistance is multiplied many times in the air volume. Higher air-temperature rises than two degrees are frequently used, but that means proportionately greater power consumption in the heater which is quite an item with large volumes. The smallness of this error with thermocouples is one of their important advantages.

In the tests referred to above, the wires in the resistance coils got covered with dirt and the added weight, combined with the effect of the air streams impinging on the enlarged surfaces, caused the wires to sag, thereby changing the resistance of the thermometer coils. As the resistance did not change equally, a very serious error was introduced. While it is true that in some meters this objection is met by more substantial construction, it also may mean greater obstructions in the paths of the gas, and usually considerably more expensive construction.

There is an advantage in the use of resistance thermometers, in that a better average of the temperatures is obtained. However, as previously explained, it is believed that with a large number of thermocouples, the error is so small as to be negligible.

Each source of error applicable to volume meters equipped with thermocouples, holds also for resistance thermometers, except that due to the escapement of heat along the thermocouple wires to the walls of the meter. However, there may be even a larger error with resistance coils, because the supports afford paths for heat flow to or from the walls, which may affect the temperatures of the coils.

It will be of value to obtain an expression of opinion from others regarding the merits of the two methods of measuring the gas temperature rise.

## Appendix III

### The Electrical Machine as a Thermal Volume Meter

In most electrical machines in which forced convection is used for cooling, an accurate knowledge of the temperature rise of the air and of the losses which produce it, should enable one to calculate the volume. Conversely, if one knows the volume and the temperature rise of the air, one can calculate the losses. Both ideas have been used. In most tests it is too expensive to provide separate volume meters. Frequently the machine losses and air-temperature rise in the machine can be used to advantage to determine the approximate volume. Even though the method is not accurate, it is extremely helpful at times when one is searching for the cause of high temperatures.

There are errors that may creep in with this method which do not appear as such in the thermal volume meter.

1. It is difficult to determine the amount of the losses that are absorbed by the ventilating air. Usually the bearing loss has little effect on the air-temperature rise, and, as it is uncertain in magnitude, it is very difficult to correct when making a single test. A method has been suggested by E. Roth[14] in which the losses and corresponding air-temperature rise are measured for two different conditions at the same speed (*e. g.*, tests at two voltages). If the friction losses are the same for both tests, the bearing loss can be eliminated by using the difference in air-temperature rises and the difference in losses. Since the result depends on the difference of quantities of the same order of magnitude, any error in the readings is magnified in the result. This may be a serious source of error because a machine has a high thermal capacity, and it takes considerable time to determine the steady state air rise. An accurate determination of the air rise is nearly impossible if the room temperature is fluctuating. Therefore, this method may lead to erroneous results.

If only one temperature test is made, and the losses determined separately, we are never certain just how much the electrical losses are. This, of course, is quite beyond the scope of the paper, and is only mentioned to indicate some of the uncertainties.

2. We usually assume that all losses go to heating the ventilating air. A small part of the generated heat escapes from the frame, or from other parts of the machine, and all that can be done is to estimate roughly the extent of such heat escapement. This heat escapement is generally by natural convection and radiation, neither of which admit of accurate calculations. Fortunately, most of such heat loss is relatively small, so that a great error is not introduced.

3. If the air temperature rise is measured where the air leaves the machine the air velocity and temperature usually vary widely at different parts of the cross-section. Under such conditions a true average temperature rise cannot be obtained. To correct this, either the velocity or the temperature must be substantially uniform over the cross-section where measurement is made. This requires special precautions in measuring the temperature rise of the air. One method of securing uniform air velocities at the point

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[14] A. I. E. E. Trans., Vol. 44, 1925, p. 905

where the temperature is to be measured is described in the paper by Laffoon and Calvert.[2] A stack was used, thereby securing nearly uniform velocities.

It has been the writer's experience that it is desirable to measure the temperature rise of the machine's ventilating air by means of a thermopile, just as for measuring the temperature rise through a volume meter. This means that a large number of wires must be used and for every thermocouple, the wires must be run from the intake to the outlet. Not less than 8 thermocouple junctions should be used at each intake assuming two intakes, meaning that there are 16 junctions at the discharge. It is desirable to increase this number.

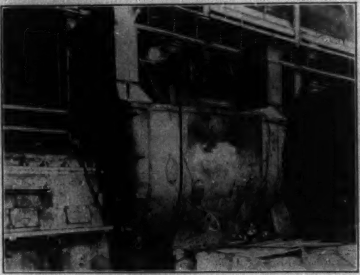

FIG. 6—A SMALL TURBO ALTERNATOR WITH VOLUME METERS ATTACHED

Thermocouples were also provided for measuring temperature rise of the air through the machine.

A turbo alternator (Fig. 6) was rigged up for testing, with volume meters and with thermocouples to measure the rise in temperature of the air passing through the machine. For simplicity of test, the machine was inverted. The large number of small wires are parts of the thermocouples.

Experience indicates that it is not well to use cotton covered wire for these thermocouples as they get covered with dirt and there is liable to be a small leakage current from one wire to another which cannot be indicated readily, and all of the readings become worthless. It is well to use higher grade insulation, such as rubber, on the wires. The thermocouple wires in Fig. 6 were cotton covered, but were subsequently changed.

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## Discussion

**W. F. Dawson:** My experiences have been very much along the lines of these authors, except that I have used resistance thermometers rather than thermocouples.

When we started we didn't use the calorimetric idea at all. We started in by attempting to measure the air velocity, and thence the air volume with manometers, and we found, as you will see by referring to an article I wrote for the *General Electric Review*, February 1920, enormous irregularities of air velocity across the inlet section. The air velocity across the outlet circuit was not quite so bad, but you will find how that might be by referring to the paper by Barclay and Smith,[1] which was prepared almost at the same time that I prepared my article.

At the suggestion of Dr. S. A. Moss, I adopted the calorimetric method. We have been going ahead with that; in fact, I make practically all of my efficiency and loss tests on turbo alternators by this method, and I cannot over-emphasize how valuable and how convenient it has been. We never could have accumulated the information for the analysis of our losses on turbo alternators if it hadn't been for this exceedingly satisfactory scheme.

I feel that a comparatively large increase in the temperature of the air as it is passing the heater coils contributes so much to the accuracy of our information that we can afford a little effect from radiation.

We did find soon after we started the experiment with the heaters that immediately they were switched on, the temperature of both inlet and outlet air was increased; I mean by that the air entering the heater and that leaving it.

Quite contrary to the arrangement shown in the illustrations in the paper, I placed this meter in the discharge pipes or conduits and when I found that we had to take account of radiant heat, we were very careful to place that heater midway between the two resistance thermometers so that the heat would affect both equally.

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[1] "Determination of the Efficiency of the Turbo Alternator," by S. F. Barclay and S. P. Smith, *Journal I. E. E.*, April 1919.

We make a log showing the effect of the radiant heat from the heater from which final corrections are made.

There is one other thing, the question of averaging the air temperatures, whether it is $H_1$, $H_2$, or $H_3$ ($H_1$ being the temperature of the air entering the machine or dynamo under observation, $H_2$ the temperature of the air as it leaves the dynamo, and $H_3$ the temperature of the air after it has passed the heater). I finally made resistance thermometers in which the copper resistance wire was wound upon wooden struts placed arbitrarily about every 4 in. and having stream line sections, spaced equally across the air passage. We pass the resistance wire between loosely cogged gears in order to corrugate it and prevent it from being strained as it is heated and cooled and then we wind it on those struts as a helix of small insulated copper wire, shellac it in place, connect all in series and calibrate the whole frame, in the Standardizing Laboratory. Then by special indicating galvanometers we read our air temperatures directly and accurately within 0.1 deg. cent.

**J. Ormondroyd:** The temperature read on the potentiometer of the air-flow meter is an average value got by a "summation of ordinates" integration. The milli-volts which would be generated in any couple depends on the position of the couple in the flow meter cross-section $V = f(x, y)$

where the center of the cross-section can be considered the origin of the $x, y$ coordinate system. The average milli-voltage $\overline{V}$ in the case where the couples are arranged in rows and columns equally spaced over the meter cross-section is

$$\overline{V} = \frac{\Sigma\,[\,\Sigma\, V_x\,\Delta\, x\,]_y\,\Delta\, y}{\Sigma\,\Sigma\,\Delta\, x\,\Delta\, y} = \frac{\Sigma\,[\,\Sigma\, V_x\,\Delta\, x\,]_y\,\Delta\, y}{\text{Cross-section area}}$$

Where the distribution is actually known $\overline{V}$ can be determined accurately by means of an experimental integration by building a solid whose upper surface represented the known $f(x, y,)$ and weighing it, for instance. In the flow meter the actual distribution depends on the disposition of the heaters, and the character of the air flow; but the couples are distributed in a fixed manner over the cross-section. The accuracy of the integration performed by the potentiometer depends on the distribution.

Tests on the small flow meter show that the distribution of the temperature over the cross-section can be represented approximately by the empirical equation $V = 65 - 7\,x^2 - 7\,y^2$

With twenty-five couples arranged in five rows in the staggered fashion used, average values in each row of couples and over the whole area are calculated by adding ordinates, and by analytical integrating. Assuming the analytical integral to be correct, the errors are as follows:

| Couple plane | Per cent error |
|---|---|
| Center........... | + 0.5 |
| Half way out..... | + 0.6 |
| Outside.......... | − 0.9 |

The average over the whole area is = 50.6 analytically, and = 51 by summing ordinates. The per cent error is 0.8.

Doing the same with 20 couples gives 0.6 per cent error; a somewhat smaller error than the larger number of couples gives, probably due to a more fortunate distribution of the couples.

When continuous resistance wires are used instead of distributed thermocouples, the errors in the planes of the wires may be considered to be zero. But in summing up five parallel wires (to compare with the 25-couple arrangement), the error is still about 0.6 per cent. The difference is not enough to be of practical importance.

The probable error in the small flow meter is in the order of ± 1 per cent. In the larger meter the distribution of temperature is not so uniform and the error may be two or three times larger.

**B. L. Barnes:** The authors have very wisely called attention to a number of sources of errors in the set-up and operation of a thermal volume meter but I believe that it is also advisable to mention a very important condition that should be taken into consideration when using a volume meter of this type to make efficiency or loss tests on large apparatus. That condition is that the temperature of the air entering and leaving the machine as well as the temperature of the machine must reach a constant value before readings can be taken for determining the losses or efficiency for the load that the machine is carrying. Large machines will require from five to ten hours to reach constant temperature at a given load and if the temperature of the cooling air entering the machine happens to be changing toward the end of that period the change in temperature of the cooling air passing through the machine is not a true measure of the losses. If the temperature of the air is rising the machine losses go to raise the temperature of the machine as well as to raise that of the air passing through. The rise in the air would be less than under a constant condition. If the temperature of the air is dropping the temperature of the machine will drop and the heat energy stored in the machine will be given out to the cooling air so that its temperature will be raised more than under a constant condition.

Several attempts were made by the engineers of the Hydro-Electric Power Commission of Ontario and by myself to carry out tests of this kind on some large generators on the Canadian side at Niagara Falls. We were never quite satisfied with the results because the temperature both in the power house and out of doors was constantly changing, and there was no way of controlling the temperature of the air as it entered the generator.

**C. J. Fechheimer:** It is interesting to learn that Mr. Hobart was one of the first to propose the idea of the thermal volume meter. It is also well to recall at this time a paper presented before the Institute in 1909 on *The Convention of Heat from Small Copper Wires.*[2] As a result of the investigations given in that early paper the hot-wire anemometer was developed.

Referring to Mr. Dawson's contribution, our views on the question of resistance thermometers versus thermocouples are covered in the paper. There is just one point on which we would comment. He claims that he measures the air-temperature rise within 0.10 deg. If the total rise is of the order of 2 deg., the possible error is then 5 per cent, which is considerable. If the air rises are much higher, the power consumption in the heater becomes considerable with large volumes.

Replying to the question raised by Mr. Barns, we also have had difficulties from variations in cooling-air temperature. This frequently is due to opening and closing of doors, windows, or the like. In some tests in a turbo alternator, the cold thermocouple junctions used in connection with the temperature rise of the air through the machine, were placed on relatively heavy copper which had fairly large thermal capacity, and somewhat reduced the effects of alterations in air temperature. But generally, where accuracy is important, the time for making tests should be so chosen as to eliminate the effects of unsteady draughts, or equivalent, upon the ingoing air temperature. The gradual changes in air temperature are usually not the causes of disturbances; the sudden changes are the troublesome ones.

It is of value to estimate the probable loss of heat from the heater coils when they are worked at high temperatures. We shall assume a heater wire 0.04 in. diameter, and calculate by means of Eq. 12 in the paper the watts per sq. in. at two temperatures and two velocities; 500 and 4000 ft. per min. The heat escapement by radiation is given by the well known equation for dull black surfaces (the wires tarnish and get dirty after being in operation for some time):

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[2] Paper by A. E. Kennelly, C. A. Wright, and J. S. Van Bylevelt, TRANS. A. I. E. E., Vol. XXVIII, Part I, p. 363.

$$\text{Watts per sq. in.} = 36.9 \left[ \left( \frac{T_1}{1000} \right)^4 - \left( \frac{T_2}{1000} \right)^4 \right]$$

Here $T_1$ and $T_2$ are the absolute temperatures in deg. cent. of the hot and cold surfaces respectively. The surface of the wire here is only the projected area, whereas that computed by means of Eq. 12 is the entire outer area. That is, for comparison, the radiated watts should be divided by $\pi$. One extreme would be if all the radiated heat were finally transmitted to the duct walls whence it escaped by conduction through the walls to the outside air. That is hardly justifiable. We shall assume a duct width equal to the distance between cold and warm thermocouple junctions, in which case there might be a possibility of about ⅛ of the radiated heat escaping. The following table is based upon all of the above assumptions, the ingoing air temperature having been taken as 25 deg. cent.

| Heater rise deg. cent. | Air vel. ft./min. | Per cent. error |
|---|---|---|
| 50 | 500 | 0.255 |
| 600 | 500 | 1.980 |
| 50 | 4000 | 0.094 |
| 600 | 4000 | 0.740 |

Thus it will be seen that at low velocities the error introduced by running the heater, at high temperature may be more than should be allowed. The error is practically negligible if the heater rise is around 50 deg. cent.

# Recent Improvements in Turbine Generators

BY STUART L. HENDERSON[1] and C. RICHARD SODERBERG[1]

Associate, A. I. E. E. Non-member

***Synopsis.**—During the last few years there has been a very rapid increase in the rating of turbine generators. That these ratings might be possible, a large amount of investigation has been necessary; and this paper covers, in a general way, some of the problems that have been studied and solved by the engineers of the Westinghouse E. & M. Co. The present status of the design of turbine generators is given, and what the future developments must be if still larger generators are to be built.*

## INTRODUCTION

THE object of the present paper is to describe some of the problems that have been encountered in the development of the turbine generator during the last five years, and to illustrate the means by which the recent increases in the ratings of the individual units have been made possible. These five years have witnessed a very rapid expansion of the size of the individual units. In 1922, the largest four-pole, 1800-rev. per min., single generator in operation, or under construction, had an output of 37,500 kv-a.; at the present time, individual units of the same speed having a capacity of 94,000 kv-a., are being built.

The general application of the cross-compound principle has brought about units of power generation having enormous outputs. The amount of power generated in the present combinations of two or three generators has reached a value corresponding to the output of a complete power plant of a few years ago. The advance made in the ratings of the individual generators is not always apparent in reviewing the outputs of the cross-compound units. The figures given in Table I indicate, however, that the increases in the rating of individual generators have been fully as striking as the increases in the ratings of complete units. In 1925, in the two-pole, 1500-rev. per min. class the maximum output of a single generator was 66,700 kv-a.; at the present time there is a generator of this type under construction having an output of 160,000 kv-a. In the four-pole, 1800-rev. per min. class, the maximum rating in 1924 was 44,400 kv-a.; at the present time, a unit of 94,000 kv-a. is being built. Thus, in both classes, the output has been more than doubled in less than four years. The figures in Table I have been given to indicate the trend of the development and do not represent a complete record of all large units that have been built or are under construction.

The construction of a turbine generator of these large sizes is a problem that encompasses practically all branches of mechanical and electrical engineering, and the achievements of today are the results of years of intensive development work of several firms and many individuals. This chapter of the history on the development of turbine generators, which is presented in this paper, will be told mainly in terms of the development work carried out by the Westinghouse E. and M. Co. It is hardly necessary to emphasize that this does not imply that this company has been the sole agency in this development, because the majority of the problems presented have been encountered and brought to a satisfactory solution by all firms active in this branch of engineering.[2]

## THE VENTILATION PROBLEM

For 1800-rev. per min. machines, the diameter of the rotor is limited (with materials commonly used), to about 55 inches, so that the increases in capacity which have taken place in the last five years have been obtained chiefly by increases in the core length. Even in the largest units built five years ago, it became increasingly difficult to supply all the cooling air from the two ends of the machine, not only because of the excessive pressure required, but also because of the increase in temperature of the cooling air as it passed through the machine. This latter factor was particularly important in long axially ventilated machines.

*Multiple radial* ventilation solved this difficulty, and it is now possible to obtain fully as uniform a temperature distribution for core lengths of 250 in. as for 100 in. The multiple radial system of ventilation is illustrated in Fig. 1. The stator laminations and vent plates are built up in a similar manner to the simple radial type. The multiple radial system differs from the simple radial in that not only can the air enter from the ends of the machine by way of the air-gap, but air can also enter the machine from the back of the core in one or more zones. In this manner a number of paths in multiple is provided. Air passes through the air-gap from the ends and is discharged through the radial vents at the end of the stator. The air entering from the back of the core flows radially inward toward the rotor, then axially along the air-gap, and then, radially outward in the discharge zones. As the length of the stator is increased, the number of intakes from the rear is increased in order to obtain uniform air velocities along the core. The introduction of cool air at a number of points along the core from the back of the core serves to give the result of a number of short machines in series, as far as air distribution is concerned;

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[1] Both of Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., February 13-17, 1928.*

[2] See Bibliography.

TABLE I

| Size of unit—kw. | No. of generators | Rating of each gen.—kv-a. | P. F. % | Speed rev. per min. | Year | Manufacturer |
|---|---|---|---|---|---|---|
| 60,000 | 1 | 66,700 | 90 | 1500 | 1925 | G. E. |
| 80,000 | 2 | 44,000 | 90 | 1800 | 1924 | Westinghouse |
| 60,000 | 1 | 70,600 | 85 | 1800 | 1925 | G. E. |
| 50,000 | 1 | 59,000 | 85 | 1800 | 1927 | Allis Chalmers |
| 88,000 | 2 | 38,000<br>64,700 | 85 | 1800<br>1200 | 1927 | G. E. |
| 90,000 | 1 | 100,000 | 90 | 1500 | On order | G. E. |
| 200,000 | 3 | 89,400<br>72,940<br>72,940 | 85 | 1800<br>1800<br>1800 | On order | G. E. |
| 110,000 | 2 | 68,750<br>68,750 | 80 | 1800<br>1800 | On order | Westinghouse |
| 160,000 | 2 | 94,100 | 85 | 1800<br>1800 | On order | Westinghouse |
| 160,000 | 1 | 160,000 | 100 | 1500 | On order | G. E. |
| 160,000 | 2 | 88,250<br>100,000 | 85 | 1800<br>1200 | On order | Brown-Boveri |

and it is no longer necessary to restrict the core length on account of ventilation. The multiple radial ventilation system was extensively investigated several years ago by Fechheimer, Bratt, and others[3] and while the system was not new at that time, an exact predetermination of the dimensions of the air circuit was not possible until the work of these men had been completed.

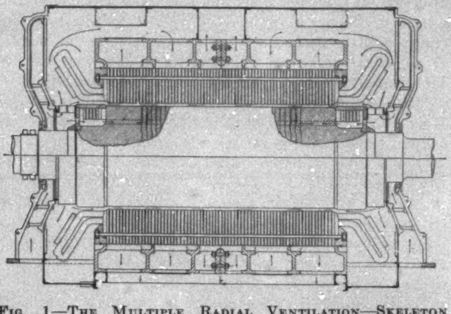

FIG. 1—THE MULTIPLE RADIAL VENTILATION—SKELETON FRAME

The detail arrangement of the stator ventilation has required considerable attention. The minimum number of ventilating ducts required to give satisfactory air distribution may result in iron packages of too great width and, in consequence, too high temperature drop through each package. Fig. 2 shows a section of the stator including two iron packages, one radial vent, and two coils with their insulation. For the distance $L$ of the coil, there are two paths in parallel for the heat to flow to the surrounding air. For the portion of the coil in the radial duct, there is a temperature drop through the insulation and a surface temperature drop; and for that part of the coil embedded in the iron, there is an additional temperature drop through the punchings. Therefore, the part of the coil in the duct will dissipate more than its proportion of the heat. In order to calculate these various temperature drops, it is necessary to determine the thermal conductivity of the

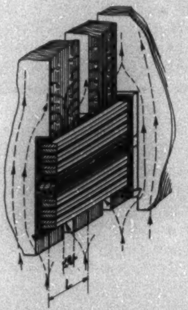

FIG. 2—HEAT FLOW IN STATOR COILS AND PUNCHINGS

built-up stack of punchings, the thermal conductivity of the insulation, and the surface drop in relation to air velocity. For the particular case shown, 30 per cent of the heat generated in the coil escapes directly to the air in the duct, although only 18 per cent of the coil is in the air duct. For a total drop from the copper to the air of 53 deg. cent., 33 deg. cent. represents the drop through the insulation, 12 deg. cent. drop through the iron, and 9 deg. cent surface drop. For that portion of the coil in the air duct, the drop through the insulation is 51 deg. cent. and the surface drop 2 deg. cent. These figures are representative for one particular type of generator and will vary for different proportions in machines, but they do show in a general way the magnitude of the different temperature drops.

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[3] C. J. Fechheimer, TRANS. A. I. E. E., Vol. 43, 1924, p. 476, *An Experimental Study of Ventilation of Turbo Alternators.*

D. Bratt, TRANS. A. I. E. E., Vol. 43, 1924, p. 467 *The Multiple Radial System of Cooling Large Turbine Generators.*

C. J. Fechheimer and G. W. Penney, TRANS. A. I. E. E., Vol. 45, 1926, p. 253, *Concluding Study of Ventilation of Turbo Alternators.*

C. J. Fechheimer, A. S. M. E., 1924, "Performance of Centrifugal Fans for Electrical Machinery."

For more than five years the project of ventilating with hydrogen generators and other large machines, has been under active consideration by designing engineers. The most important advantage connected with this use of hydrogen is reduction in windage loss; in an 1800-rev. per min. generator of the maximum sizes under consideration, this is the largest single loss in the generator, and may amount to as much as one percent of the kw. rating. But there are obvious practical difficulties in building a sufficiently gas-tight structure and these practical problems have, up to a very recent date, prevented the accomplishment of this interesting development.

While there have been no machines actually installed using hydrogen as a cooling medium, several turbine generators have been sold with the provision that hydrogen may be used later, and a large synchronous condenser has recently been sold for immediate installation with hydrogen cooling. Experimental work is being actively conducted, and the Westinghouse Co. has an experimental 7500-kv-a. generator operating with hydrogen cooling. The decrease in friction and windage loss, and the possible increase in rating due to better heat transfer in a hydrogen atmosphere, make the use of hydrogen most attractive. It is the opinion of the authors that it is only necessary to demonstrate to operating engineers the safety of machines ventilated by hydrogen, when there will be another general step upward in efficiency and rating. In order to gain the most from hydrogen cooling, the design proportions must be changed to suit the new conditions. The arrangement of the ventilating ducts should be different, since higher velocities can be used advantageously. Then too, the proportions of rotor and stator strength must be altered if the same short circuit ratio and stability is to be maintained. For these reasons it would not be possible to change existing air-cooled machines to hydrogen-cooling, and materially increase the rating without making other fundamental design changes.

### DESIGN OF STATOR COILS

In order to build machines of extreme core lengths for these large ratings, it became necessary to modify the design of the stator coils. On shorter machines, it has been customary to build the coils in one piece as shown in Fig. 3. This type of coil is continuous from the front, without any connections in the rear. Such a coil has the advantage of being turned over in the rear-end connections; that is, the top conductor of the top coil in one slot becomes the bottom conductor in the bottom coil in the return slot. This provides partial transposition against eddy currents and when additional transposition is provided at the front of the coil, the additional losses due to eddy currents can be reduced to less than 30 per cent of the copper loss. Long coils of this construction may weigh as much as 350 lb. and are therefore difficult to handle in the insulating process and in winding the coils in the core. This makes it desirable to construct them in halves and connect them on the front and rear. If it were possible to connect each strand individually at the rear, the structure of the half coils would be the same as full coils so far as eddy current loss is concerned; but for deep coils with many strands, such construction is impossible because of insufficient room to make all the connections. It is necessary, therefore, to transpose the strands somewhere between the front and the rear of the machine. This is most easily carried out in the straight or buried part of the coil.

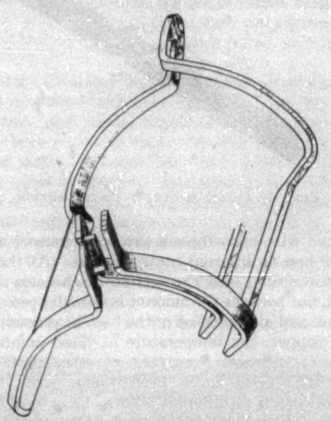

FIG. 3—ONE PIECE STATOR COIL

There are several different methods by which this can be accomplished. The method used on the large machines designed by Westinghouse engineers is a combination of transposition of strands within the slot, and transposition outside the slot at the ends of the coils. Any one conductor in the coils is split up into groups of several strands in depth and the strands in each group are transposed within the slot to eliminate the eddy currents between the strands in the group. The groups are then transposed with respect to each other at the front end of the coil to eliminate the eddy currents between the groups. The strands in a group may then be soldered together at the front and rear using a single joint. This arrangement reduces the transposition of the strands within the coil and simplifies the construction. One group and the detail of one strand is shown in Fig. 4. The transposition points are stamped out with a compound die. Each strand is insulated with mica tape in the same manner as when the coil had no internal transpositions. At the points of transposition, half the section of the strand is removed, but because the amount is a small percentage of the total and also because of the high heat conductivity of the copper, the temperature at these points is not materially different from that at other parts of the conductor. Tests have been made with thermocouples located at different points on the coil, but the variation was no greater than could be expected in a simple conductor of uniform section.

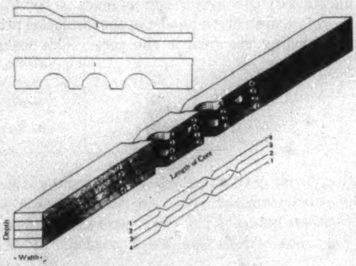

FIG. 4—INTERNAL STRAND TRANSPOSITION

The question of armature coil insulation has been given considerable study in preparation for these larger units. The stator coils on Westinghouse machines have been insulated for a number of years with a mica-folium wrapper on the straight parts and treated tape on the ends of the coils. The individual strands in the coils and the conductors have been insulated with mica tape throughout their entire length. The insulation on the end turns has given good service and the same type of insulation has been used on water-wheel machines up to 18,000 volts. The advantage of the treated tape on the end is that it is flexible and can withstand the slight movements of the coil ends that will occur on short circuit. The seal between the mica-folium wrapper and the treated tape has proved satisfactory. While it has been criticized as a point of possible weakness, there has never been a failure at this point.

An improvement in the mica folium has been made to correct swelling and wrinkling of the insulation. Research work revealed the cause of swelling to be due to the vapor pressure caused by the alcohol in the shellac bond of the mica and, to some extent, to moisture in the paper used for backing the mica. A large number of sample bars was wrapped under different manufacturing conditions and with different classes of material. The bars were then placed in an electrically heated oven, some with voltage applied and others with no voltage. Readings were taken to determine the amount of swelling and temperature. The difference in temperature of the coils with voltage impressed and the temperature of the oven gave a relative measure of the dielectric loss.

In Fig. 5, there is shown one of these sample bars in the oven as arranged for test. The bars were made up of square, hollow tubes and thermocouples were applied to the inside surface of these tubes. Plates were clamped on the coils, to represent the iron laminations, and gaps left between the end of the plates to represent the radial ducts.

The result of these tests led to the development of a new bond that practically eliminated the cause of insulation swelling. A comparison of the dielectric loss, as expressed by temperature rise above the oven temperature for coils with shellac bond and with the new bond, at various oven temperatures, is shown in Fig. 6. Three curves are shown covering two grades of shellac and the so-called black bond. It is evident that the dielectric loss for the black bond increased but slightly with temperature, while the two bars with mica using a shellac bond showed an increasing dielectric loss with rising oven temperatures.

FIG. 5—EXPERIMENTAL SPECIMEN OF COIL ON TEST

The use of this new bond resulted in a wrapper which was more flexible. This characteristic made it possible to build in additional sheets of mica which increased the dielectric strength of the wrapper. Coils wrapped with insulation for 22,000-volt operation have withstood a momentary test of 160,000 volts.

In preparation for higher operating voltages than 13,800, the use of a special coating for the outside of the coils has been developed, to decrease the corona between the sides of the coils and the sides of the slots. If a perfect contact could be made between the coil and the sides of the slot throughout the length of the slot, corona would not exist. This ideal condition, however, cannot be reached because of manufacturing variations in the width of the slot, and in the width of the coil. If the coil touches the slot only at points, then there will be corona from those points of the coil which do not touch. A semi-conducting film is therefore required on the surface of the coil so that all points on the surface will be at ground potential. Fig. 7 shows an experimental set-up to demonstrate the effectiveness of such a conducting film. On each coil there was placed a stack of punchings to represent the stator iron, and 30,000 volts were impressed between the copper and the iron. The bottom coil (I) shows the corona on a coil without grounding film. The middle coil (II) shows a comparison of a coil with and without the protecting film, the middle of the coil being coated. The top coil (III) shows a method of damping out the corona at the ends by using a coating of somewhat higher resistance beyond the core. This test was made at higher voltage to ground than normally obtained in the machine in order to demonstrate more effectively the benefit obtained from the use of a grounding film.

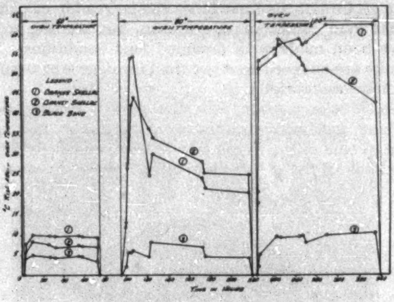

Fig. 6—Temperature Tests on Turbo Alternator Coils

The question of higher voltages for generators is receiving attention on these larger units. A unit of 100,000 kv-a. can be built for 13,800 volts, but the cost of circuit-breakers, switches, and bus-bars may make it desirable to build such machines, especially in new stations, for terminal voltages as high as 22,000. The machines for one station are being built for this voltage. Such machines must meet a final insulation test of at least 45,000 volts before going into service. To prepare for this final test, it is necessary to test the coils at considerably higher voltages after they are placed in the slots, but before they are connected. For lower-voltage machines these preliminary tests are made with the ends, where the connectors are applied, uninsulated. With these higher voltages, however, the discharge will creep along the surface of the coil from the exposed ends to ground if the voltage is applied for a minute. With such high voltage tests in air, a certain amount of fireworks must be expected.

*General Design.* With the increase in the size of the individual units has also come improvement in efficiencies. In the past the stator laminations were made from non-silicon steel. There was a prejudice against silicon steel in rotating apparatus because of brittleness, the fear being that the stator teeth would break off due to vibrations. Improved methods of building stator iron and better design of finger supports have removed the danger of loose iron and consequently, the danger of vibration. Furthermore, vibration life is a function of the endurance limit of the material and because this is higher for silicon steel, it also has a greater vibration life. The early troubles in the use of silicon steel were associated with the use of fillets with too small radius at the bottom of the slots, which resulted in incipient cracks during punching. These fillets have been increased in radius and this trouble has been eliminated.

Many machines have been built with two per cent silicon steel; and more recently four per cent silicon steel has been generally used. In other words, turbine generator stators are now built with a grade of steel which is equal to the best steel used in transformers. The high-grade, four per cent, silicon steel sheets have more scale than the two per cent and non-silicon steels and, therefore, must receive special treatment to remove the scale. It is possible, by special treatment, to obtain the same space factor with the four per cent steel as with the lower grades.

To illustrate the reduction in core loss that results from the use of these higher grade steels, if the loss in non-silicon steel be represented by 100, the loss with two per cent silicon steel will be 70, and 45 with four per cent silicon steel. The use of four per cent silicon steel improves the efficiency slightly more than one per cent at full load, and two and a half per cent at half load, as compared with the efficiency of machines using non silicon steel. When this steel is used the

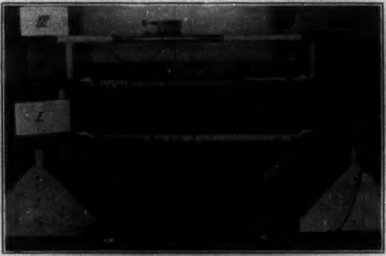

Fig. 7—Corona Elimination

core loss is reduced from 50 per cent of the total loss to 30 per cent of the total loss.

A new trouble that has appeared in these larger machines, is heating of the finger plates which support the stator teeth. This heating is most noticeable on machines with high ampere-turns per slot, and on machines with full pitch or two-thirds pitch windings. For these two classes of windings the hottest fingers will be those between phase groups; and this might be expected since these are the teeth in which the leakage flux flows in a radial direction along the teeth. The flux distribution is also affected by the nearness of the rotor retaining ring and magnetic saturation of the retaining ring. A study of the flux distribution at the end of the machine has been made, using the methods developed in the papers presented at the 1927 Winter Convention of the Institute. The flux causing this heating can be controlled by proper proportions of the finger plates and retaining rings or, if this is not possible, by the use of non-magnetic manganese steel in the finger plates. The use of non-magnetic steel in the retaining rings is also beneficial under certain conditions.

The questions of short-circuit ratio and regulation of turbine generators have not been of serious moment in the past, largely because turbine generators are usually installed near the center of load, and problems connected with long distance transmission have not arisen. The problem has received attention recently on those systems which do not use automatic voltage regulation, and where the capacity of the individual units is large in relation to connected load. In such a station with only a few units in service, the failure of one unit may throw a heavy load on the other units, and power stability may become important. The investigation has been made on the basis of constant field current and, consequently, decreasing voltage. Whether machines will be unstable on the basis of constant field current depends on the design of the generator and also on the system characteristics. Short-circuit ratio and degree of saturation in the generators are of importance, but it is just as necessary to know the variation of the load with change in voltage. With a lighting load, the current and kilowatts will decrease with voltage; while with an induction motor load the kilowatts will remain practically constant, the current will increase, and the power factors will improve with decrease in voltage to a point above the pull-out point of the motors. Usually, an estimate must be made of the proportions of lighting and power load and this estimate has an important influence on the conclusions. Machines are in operation in this country with short-circuit ratios as low as 0.8 and large machines in general have short-circuit ratios between 0.9 and unity and, so far as we are aware, there have been no cases of instability which could be traced to generator design proportions. The cost of generators increases, with increase in short-circuit ratio. In Europe, short-circuit ratios as low as 0.5 are in use and this fact partially explains the high ratings that are obtained on 50-cycle 3000-rev. per min. machines. It is desirable, therefore, that specifications should not call for unnecessarily high short-circuit ratios, because this will limit the maximum possible size of generator, and will increase the cost per kilowatt. More definite information is required concerning the performance of systems with change in voltage, in order to establish more definitely the safe lower limit of short-circuit ratio. The performance of machines can be readily calculated if the load conditions are known, but studies, so far, have been made with assumed load conditions. The results are no more accurate than the degree of accuracy of these assumptions.

*Stator Construction.* In the earlier constructions, turbine generator frames were made of cast iron. The section of the frame was determined chiefly by the demands of the stator-ventilation system, because the casting included the ducts for conducting the cooling air to and from the core. A frame of this type is shown in Fig. 8.

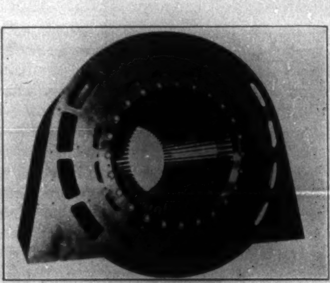

FIG. 8—CAST IRON FRAME WITH PUNCHINGS

One of the most serious objections to this construction is that it leads to frame widths too great for shipment with usual railroad clearances. For the longer core lengths, it would be necessary to ship the stator in parts and carry out the assembly and the winding at the power station. Another objection to the cast frame is the excessive weight. The rigidity and the strength of the frame are far greater than required by the stress conditions to which it is subjected in handling and in operation.

These objections led to the separation of the frame in two parts; a super-structure of light, structural steel for the air passage and a skeleton frame for carrying the core. An analysis of the requirements of strength and rigidity was made in 1925[4] and it was found that the requirements from this point of view permitted a considerable reduction in the depth of the cast frame section and in the total weight.

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[4] M. Stone, "Stresses and Deflections in Large Dynamo Frames," A. S. M. E., Dec. 1926.

Fig. 9 shows a frame of this type, with a part of the structural steel super-structure mounted on the outside. This super-structure is fitted at the factory, removed for shipment, and re-installed at destination.

This improvement in stator construction reduced the weights of the heaviest pieces to be shipped approximately 30 per cent, and the installed weight of the stator approximately 15 per cent.

With this construction it is possible to build the core and complete the winding at the factory, and still maintain the width within shipping dimensions. The Pennsylvania Railroad assisted in solving this problem of shipment by building two depressed cars, each capable of carrying a load of 275,000 lb.

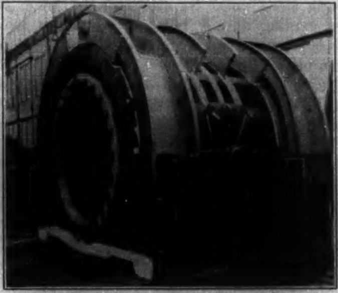

Fig. 9—Skeleton Frame Construction

It was but another step to build the skeleton frame of structural steel as well, and this has been done in the latest constructions. This structural design has decreased the weight of the stator another ten per cent, and raised the limit of capacity of machines that can be built and wound at the factory from 75,000 kv-a. to approximately 100,000 kv-a.

## Mechanical Construction of the Rotor Body

*General Conditions of Stress. Working Stresses.* The rotor body is subjected to stresses from three major causes: The centrifugal forces, producing radial and tangential stresses; the bending forces (gravity and dynamical forces), producing longitudinal stresses; and the torque, producing shearing stresses. The relative importance of these three causes varies with the type of machine, but up to the present state of the development only the centrifugal stresses, and the bending stresses, have played an important role in limiting rotor dimensions.

The centrifugal forces alone cause critical stresses, either in the radial direction at the bottom of the teeth, or in the tangential direction at the inner bore. The relative magnitude of the former is usually much greater than the latter, but when the rotor is made of a one-piece forging the latter may be more important than the former, on account of the uncertain properties of the material at the inner bore. In the built-up plate rotors, where this uncertainty of the material does not exist, the radial stress at the bottom of the rotor teeth is the true critical stress.

This cross section must carry the centrifugal forces from the teeth themselves, from the coils, and from the wedges, the latter groups being magnified by the wedging effect of the rotor wedges. This magnification can be eliminated almost completely by the use of rectangular wedges (Figs. 10A-B), but the gain is offset, to a certain extent, by the increased amount of material necessary above the wedge.

The stresses in the coil retaining rings, due to centrifugal forces, are almost exclusively tangential so that, although the nature of the design demands a very high stress in these rings, there is less difficulty in establishing the actual stresses in the coil retaining rings than in the rotor body; and the selection of a safe working stress is easier.

The bending stress in the various parts of the rotor body is alternating and for this reason very important, even if the value of the stresses, in comparison with the centrifugal stresses, is small. The building of long rotors, necessitating higher values of these bending stresses, has further accentuated this problem. Before the rotor length increases of the last five years had taken place, the maximum bending stress occurred at some part of the shaft near the bearings, and the bending stresses in the middle body were very small. The gradual lengthening of the rotors has changed this situation somewhat; the bending stresses near the bearings have not been reduced, but the bending stresses in the middle body are now of the same order.

This is particularly true of the one-piece rotors where circumferential grooves are turned down to the bottom of the slots to provide radial exhaust ducts from the axial air passages. This increases the bending stresses and causes stress concentration. Probably the most important aspect of these bending stresses in the middle body of solid rotor forgings is the fact that they exist in conjunction with a certain tangential centrifugal stress. This introduces a two-dimensional condition of stress, of which one component is variable and the other stationary (Fig. 11). The failure of the material

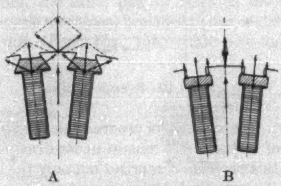

Fig. 10—Conditions of Loading on Rotor Teeth
A—Dove Tail Wedge
B—Rectangular Wedge

is dictated by the extreme value of shear stress in the plane of maximum shear. In this plane the stress conditions may be considered as consisting of an average stress, upon which is superimposed a variable stress. (Fig. 12.) By this reasoning the state of stress is reduced to a form, for which failure can be predicted in terms of the properties of the materials in pure tension.

In the built-up plate rotors, air outlets can be provided without material reduction in the section modulus, so that the longitudinal bending stresses and the tangential stresses do not occur at the same points. In these rotors the critical bending stress will probably occur at the sections next to the middle body (under the end windings) for rotors of great length. Here the tangential stresses due to centrifugal forces are small, so that the application of stress is practically one-dimensional, with complete reversals.

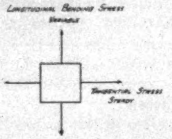

Fig. 11—Two-Dimensional Stress Applications

The question of safe working stresses is a most important one, both from the point of view of safety and economy. A great deal of progress has been made but a number of features still remain under discussion. The scope of this problem comprises not only the considerations of the practical designer, and the results of the theory of elasticity, but also the point of view of the metallurgist, and it is only through complete coordination of these three branches of engineering that a satisfactory point of view can be attained. The following represents the attitude taken by Westinghouse engineers at the present time:

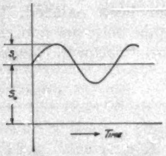

Fig. 12—Stress Cycle

In cases of steady stress in ductile materials, the *yield point* is regarded as the fundamental basis for the selection of the working stress. The factor of safety is thus expressed as the ratio of the yield point of the material, to the stress. The failure of the material at the yield point is caused by shear (maximum shear theory),[5] so that in cases of combined stresses the maximum shear stress is the determining factor in expressing the factor of safety. Conditions of stress concentration are generally disregarded for all cases of steady stress in ductile materials.

In cases of variable stresses in ductile materials, the *endurance limit* for complete reversals is regarded as the fundamental basis for the selection of the working stress, and the factor of safety is expressed as the ratio of the endurance limit to the maximum value of the alternating stress. Failure is attributed to maximum shear in this case also, but here it is necessary to introduce the conditions of *stress concentration*, so that the working stress must be expressed as the maximum stress existing at any point of the structure. This stress is generally two to three times that calculated by elementary formulas.

In cases of combination of a static stress, and a variable stress, (Fig. 12), the available experimental results[5] are used with certain modifications. It has been found that these experimental results are applied in a logical manner if the actual factor of safety is regarded as the combination of an imaginary factor of safety $n_0$, existing when the static stress is acting alone, and another imaginary factor of safety $n_v$, existing when the variable stress is acting alone. The actual factor of safety $n$, is then expressed by the relation

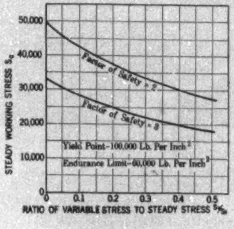

Fig. 13—Example of Working Stresses for Simultaneous Application of Steady and Variable Stress

$$\frac{1}{n} = \frac{1}{n_0} + \frac{1}{n_v}$$

In this manner it is possible to define the maximum static stress, which can be applied when its exists in conjunction with a certain variable stress. Fig. 13 is an example of such a curve of working stresses for a 3½ per cent nickel steel.

It is evident from the above that the only material properties, upon which the designs are based, are the yield point and the endurance limit.

This by no means implies that the remaining properties of the materials (ultimate strength, elastic limit, elongation, reduction of area, and impact tests are left

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5. See, for example, Timoshenko and Lessells, "Applied Elasticity," p. 477.

out of the picture); the consideration of some of these quantities is equally vital to the soundness of the design, but unfortunately, it is only in a qualitative manner and they find expression in the design proportions and in the material specifications.

Probably the most important of these "qualitative" considerations are those which refer to the ductility and toughness of the materials. The elongation, measured on two-in. gage length, is still the chief element in this connection, but, since the distribution of the flow in the test piece does not find its expression in this term, it is equally important to consider the reduction of area, which expresses the maximum value of the unit elongation when failure occurs. But even these two terms in conjunction give insufficient information about the true cohesive properties of the materials; these are expressed by the impact test on notched bars. The controversy among metallurgical experts on the true value of the impact test still makes the designer hesitate in placing implicit faith in the impact test values, but there is very little doubt that they will play an important role in the future. At the present time the chief value of the impact tests is to furnish a check on the uniformity of the heat treatment of the material, not readily obtained by any other method.

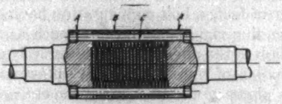

FIG. 14—LONGITUDINAL SECTION OF PLATE ROTOR

The present attitude of the designers is to place the lower limit of the elongation of the materials in the rotor body at about 20 per cent, and the reduction of area at about 40 per cent. These limits have been established by experience, and when the arbitrary nature of the constants (particularly the elongation) is considered, there is a certain justice in raising the question whether these limits really do represent the lowest safe values that can be used. The question is not without its importance because the above limits represent the chief obstacle in obtaining one-piece forgings for large rotors. On the other hand, the risk is too great to propose radical changes in these limits until more knowledge is available.

A similar situation exists in connection with the location of the test pieces on solid rotors. The attitude of Westinghouse engineers with regard to solid forgings is to judge the quality of the material by radial, tangential, and longitudinal test specimens. This severe specification again adds to the difficulty of obtaining large one piece forgings, but in view of the statements above on the principal stresses in the rotor, it does not seem wise to modify this demand.

The designer who desires to employ very large forgings is faced by difficulties. He can insure reasonable safety by specifying complete radial, tangential, and axial tests and by maintaining fairly high limits for elongation and reduction of area; the result will be a high price for the material; or he can buy on routine, material specifications and assume the liability for the cost of unsuitable forgings.

*The Westinghouse Plate Rotor*. The limitations of one piece forgings for large rotors were anticipated at an early date by the Westinghouse Co., and their present construction was originated by Behrend and Fields[6] over eighteen years ago. It will be referred to as the *plate rotor*.

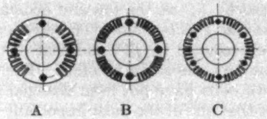

FIG. 15—ARRANGEMENTS OF THROUGH BOLTS

The rotor consists of two forgings *A*, (Fig. 14), which furnish the shaft ends, and a certain small portion of the middle body. The remainder of the middle body is made up of plates, *B*, which in the earlier constructions had a thickness of about two in. In some of the latest designs, plate thicknesses up to 8 in. have been used. These plates are spigoted into the end forgings, and into each other, so that adequate centering is obtained. The portions of the plate inside this spigot-fit are relieved, so that only the outer portions of the plates carry pressure. The entire structure is held together by through bolts, *C*, tightened to give a certain initial pressure. The number of bolts is four for two- and four-pole machines, the extra pair of bolts in the former (usually 25-cycle machines) is placed in the center of the slotted portion (Figs. 15A, 15B). Six pole machines have six bolts, placed in the centers of the poles. Fig. 15C.

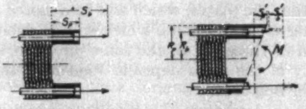

FIG. 16—LOAD CONDITIONS ON CROSS SECTION OF PLATE ROTOR

In order to appreciate the possibilities and advantages of this construction, it is necessary to discuss the fundamental principles of its performance.

Fig. 16A shows schematically the loading conditions on a section of the rotor, when no external bending moment is acting. The compressive stress of the plates, $S_p$, counterbalances the tensile stress of the bolts, $S_b$, so that if $A_p$ and $A_b$ are the respective areas (Figs. 17, 18) it is necessary that

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[6] *Some Difficulties of Design of Turbine Generators*, A. B. Field, JL. A. I. E. E., Vol. 54, 1915, p. 65.

B. A. Behrend, TRANS. A. I. E. E., Vol. 36, 1917, (Discussion) p. 883.

$$S_p = \frac{A_b}{A_p} S_b$$

Fig. 16B represents the loading of the same cross-section when it is subjected to an external bending moment $M$. The compressive stress on the plates is now increased by $S_p'$ at the top and decreased by the same amount at the bottom. The stress of the top bolt has been reduced by $S_b'$, and that of the bottom bolt increased by the same amount. The stresses of the other two bolts have not been changed materially. It is evident that one of the most important limitations of the structure is that the diminution in stress of the plates and the bolts must not reduce the stress to zero at any point, otherwise a condition of discontinuity will occur. It was found in the earliest applications of the structure, however, that there are no difficulties in securing this condition. As a matter of fact, no machine has been constructed where the variation in plate stress exceeded 20 per cent of the initial stress, or the variation in bolt stress exceeded 4 per cent of the initial stress.

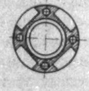

Fig. 17

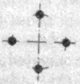

Fig. 18

Figs. 17 and 18—Plate Area and Bolt Area

It is evident from Fig. 16B that the external bending moment $M$ is counteracted by two internal moments, a moment from the plates, which will be denoted by $M_p$, and another from the bolts, which will be denoted by $M_b$. Both of these act in the same direction, so that the rigidity of the rotor depends upon both the plate area and the bolt area.

In order to determine the rigidity accurately, it is necessary to take into account the variation of the external bending moment along the length of the rotor. It has been found, however, that it is sufficiently accurate to assume that the bending moment is constant for the entire middle body, that is, for the entire length of the bolt. With this assumption it is easy to compute separately the extension of a bolt, and the extension of a corresponding fiber in the plate column. The values of the bending moments $M_p$ and $M_b$ are obtained from the fact that these extensions are equal. The plate stress, at the radius $R_b$ is $M_p/I_p . R_b$, where $I_p$ is the moment of inertia of the plate area (Fig. 17). The extension of a fiber along the middle body of length $a$ is consequently $M_p/E\,I_p \times R_b \times a$. The modulus of elasticity $E$ is that of the plate column; so long as the compressive stress exceeds about 5000 lb. per sq. in., this has been found to be the same as that of the plate material. The extension of a bolt is similarly $M_b/E\,I_b \times R_b \times a$ where $I_b$ is the moment of inertia of the bolt area (Fig. 18). Consequently

$$M_p = \frac{I_p}{I_b} . M_b$$

Now, since $M_p$ and $M_b$ counteract the external bending moment

$$M = M_p + M_b$$

so that

$$M_p = M \frac{\frac{I_p}{I_b}}{1 + I_p/I_b} \text{ and } M_b = M \frac{1}{1 + I_p/I_b}$$

For the ordinary four-pole machines, $I_p \cong 8\,I_b$, so that the bending moment carried by the bolts is actually very small; about 11 per cent. The bolts furnish mainly the static pressure between the plates. As a matter of fact, a bolt configuration having practically no bending rigidity of its own, such as the case of a single bolt in the middle, would be entirely practical from this point of view. The only difference would be that the plates would then carry the entire bending moment, that is $M_p = M$.

The actual deflection that is obtained under the external bending moment $M$ is now easily calculated. For simplicity we may calculate the actual extension of a bolt, or a fiber of the plates at the radius $R_b$. This is

$$\frac{M_p}{E\,I_p} \times a \times R_b = \frac{M}{E\,I_p} \times \frac{\frac{I_p}{I_b}}{1 + \frac{I_p}{I_b}} \times a \times R_b$$

$$= \frac{M}{E\,(I_p + I_b)} \times a \times R_b$$

showing that the rigidity of the rotor is determined by the moment of inertia of the plate area, plus that of the bolt area. This is an important feature of the plate rotor, in that the rigidity is not reduced by cutting out the holes for the bolts. In cases of very large variations of the bending moment over the rotor length (very long rotors), this statement must be modified slightly; but the error in using the entire plate area, including the bolt holes, in computing shaft deflections, is never more than about 2 per cent.

It is evident from this that the critical speed of a plate rotor is practically the same as that of a solid rotor having the same effective area. In view of the practise of turning circumferential grooves in the solid rotors for ventilation purposes it may even be said that the plate rotor, for the same ventilation arrangement, furnishes greater rigidity than the solid rotor.

From this fact it follows that the variation in stress, to which the bolts are subjected, is also very small. It is evident that the variation in bolt stress is exactly the same as that of a corresponding fiber of a solid rotor of the same cross-section. This stress is always very small,—it is only in the very longest rotors that it reaches 1000 lb. per sq. in. If it is remembered that the assembly stress is usually about 40,000 lb. per sq. in., it will be understood why this stress variation can be neglected.

The variation in plate stress is somewhat larger, but even this is negligible. The maximum bending stress of the middle body, recorded so far, is about 1500 lb. per sq. in., while the assembly stress is usually above 8000 lb. per sq. in.

The theory has been advanced several times that the plate rotor would furnish appreciably damping to vibrations, due to friction between its parts. It is evident from the above that the only friction occurs between the bolts and the plates, and only when the bending moment varies an appreciable amount over the middle body. Special tests have been made to determine this difference in damping between a solid rotor and a plate rotor, but no such difference has been observed. In fact, cases are on record where the internal damping of a plate rotor was less than that of a solid rotor of the same size. Nor has any change in plate rotors been observed in this respect after several years of service.

As a conclusion to the above discussion of the mechanics of the plate rotor, it can be stated that the plate rotor does not possess any limitations to increases in rotor length other than those furnished by the limitations of shaft deflections and critical speeds. In this respect, it is on par with the solid rotor. Its inherent advantages are due to the possibility of using high grades of steel, independently of the size of the rotor body, and the better possibilities of rotor ventilation.

*Development of Rotor Materials: Large One-Piece Forgings.* The attitude of the manufacturers with regard to the relative merits of one piece forgings and the sectional constructions has undergone important changes in the last two or three years. It is only a short time ago that most turbo designers were convinced that a satisfactory one-piece forging could be obtained for any of the rotor dimensions within sight, if the price were forthcoming. The latest advances in the size of individual units has changed this condition; the present maximum sizes of rotors can no longer be built of one-piece forgings, regardless of price and specifications.

The development of the plate rotor has been brought to a point where it is competitive in price even for rotors of about 75,000 lb. in weight; so that the conclusion that a plate rotor is necessarily more expensive than a one-piece forging is no longer true.

The art of making large one-piece forgings will continue in its development, however, and a few advances may easily upset these relative positions. Then, too, the plate rotor demands forgings of a respectable size for the shaft ends, so that no manufacturer of large turbine generators can afford to be out of touch with the forging situation. It may be of interest, therefore, to review very briefly some of the problems encountered in preparing a one-piece rotor forging for a 37,500-kv-a. generator, weighing about 130,000 lb.

The first forging attempted for this machine, was brought through in 1923. The ingot was cast from three heats of varying carbon content; the bottom heat having 0.45 per cent, and the top heat 0.29 per cent. The ingot weighed 217,000 lb., and a top discard of 79,000 lb. was made before forging.

After the forging operation it was given a heat treatment consisting of 1600 deg. fahr. normalizing heat, followed by lower temperature treatments.

At this stage, tangential tests, taken from the ends, showed a yield point of 31,000 to 33,000 lb. per sq. in., an elongation of 10 to 19 per cent, and a reduction of area of 12 to 30 per cent. This was unsatisfactory, and two additional heat treatments were undertaken with somewhat higher normalizing temperatures, after which a complete series of tests was made in the radial, tangential, and longitudinal directions. All test pieces, with the exception of one, showed satisfactory properties, with elongation above 20 per cent and reduction of area of about 40 per cent. The exception was a tangential test from the top end of the forging; it gave a yield point of 44,000 lb. per sq. in., an elongation of 9 per cent, and a reduction of area of 11 per cent.

When the forging was turned, subsequently, concentrations of slag pockets were observed near the first shaft fillet on the top end of the forging. The forging was rejected on the strength of this discovery, and subjected to a series of tests. The slag pockets were found to extend into the forging, and a chemical analysis established that carbon segregation had taken place. The carbon content at the top end of the forging was found to be 0.62 per cent, and at the bottom end, 0.26 per cent, showing a reverse condition from that in the ladle analysis.

A second one-piece forging for the same size of machine was brought through in 1925. In the preparation of this forging special care was applied throughout, and the pouring into the ingot was made with basic steel at the bottom, and acid steel at the top. The ingot was not allowed to cool below a cherry red heat, before which it was transferred into the forging furnace. Special precautions were taken in the forging operation, such as v-tooling before necking, and a very careful adjustment of the reductions obtained in each operation. The heat treatment consisted of a high normalizing heat of 1750 deg. fahr. followed by additional lower temperature treatments. One important improvement was hollow boring of the forging before the final heat treatment, not only to facilitate bore search, but to procure greater uniformity of temperature and faster penetration of the heat.

The test results showed uniformly satisfactory properties in the three directions with a yield point of about 30,000 lb. per sq. in., an elongation of about 32 per cent, and a reduction of area of about 55 per cent. The endurance limit was found to be about 27,000 lb. per sq. in.

It is evident that perfectly reliable forgings can be obtained only through the application of the greatest care and the utilization of the latest advances. The performance related for the second forging has been repeated subsequently on smaller forgings, but this special treatment raises the price to a point where one-piece forgings cease to be competitive with the plate construction.

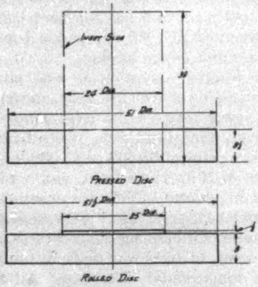

Fig. 19—Forged and Rolled Turbo Plates

The question of test procedure is of vital importance in this connection. If the demand on ductility can be waived, particularly for the tangential direction, the price of one-piece forgings can be reduced considerably, and it may be possible to raise the yield point. Whether this can be done without too much risk, is a question which must remain open until more knowledge of the factors which contribute to failures are available.

*Materials for Plate Rotors.* The earliest constructions were made up of 2¾ in. *rolled plates,* machined to a thickness of 2 in. The material was rolled out in slabs, large enough to give six rotor plates with ample discard on the sides and on the ends. The material was 30 per cent carbon steel with a yield point of about 40,000 lb. per sq. in., elongation of about 26 per cent, and a reduction area of about 45 per cent. The material itself was fairly inexpensive, but the machining cost was high on account of the great number of surfaces in a rotor. The directional alignment of the structure, due to rolling, was pronounced, so that certain variations in ductility were obtained parallel to, and at right angles to, the direction of rolling. In addition, it sometimes possessed considerable internal stresses.

A nickel steel (about 3½ per cent Ni) was used in a number of machines, where it was desirable to have a yield point somewhat higher than that of the carbon steel.

The development of a thicker plate material, having a more favorable structural alignment, was started a few years ago by W. J. Merton.

The first attempts consisted in obtaining a plate which was pressed out from a cylindrical ingot and subsequently rolled out in a tire mill, (Fig. 19). Probably the most important advancement in the new practise was a heating of the disks above forging temperature, followed by a normalizing treatment, and then by an annealing, relieving the internal stresses.[7] The importance of this heat treatment is seen from the fact, that while the plate, as rolled, had an elongation of four per cent and a reduction area of 8 per cent, after the final treatment these values were brought up to 20 per cent and 36 per cent, respectively. The yield point remains practically unaltered, at about 46,000 lb. per sq. in.

By this method it was possible to produce carbon steel plates of a thickness up to about 8 in., having in some respects properties superior to the flat rolled plates, at a price only slightly higher than that for the flat rolled plates. The increase in price was more than offset by the reduction in machining.

Fig. 20—Micro Photographs of New Plate Material

The next step in the improvement of the plate materials was obtained by piercing the pressed disk and carrying out the remaining operation by forging on a mandrel, instead of rolling. The heat treatment consists of a thorough annealing above finish-forging temperature, a reheating and quenching in water, and then additional reheating for drawing.

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[7] W. J. Merton, American Society for Steel Treating Ninth Annual Convention, Sept. 1927.

By this process it has been possible to obtain *a yield point of about 65,000 lb. per sq. in.*, an elongation of 25 per cent, and a 50 per cent reduction of area in disks of 0.45 per cent carbon steel. The properties in the tangential and radial directions are practically the same, and the material has an extraordinarily fine grain structure, as shown in Fig. 20. The micro-photographs (from which the figure was made) were taken from three different plates. Fig. 21 gives an external view of one of these plates after rough machining.

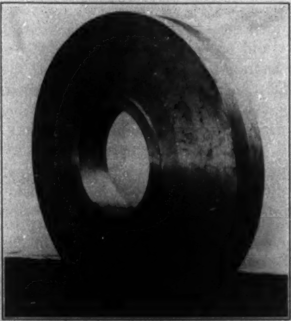

FIG. 21—HEAT TREATED ROTOR STEEL DISKS

The development of this material represents a most important contribution of the metallurgists to the solution of the problem of designing these extremely large size units. Its use has enabled the designer to maintain ample factors of safety, to increase the output from a rotor of given over-all dimensions (because of superior strength of the material), and to lower the over-all cost.

It is not possible, so far as the authors know, to obtain material of this quality, in carbon steel forgings for large size rotors (over about 75,000 lb.), at any price. The possibility of obtaining it at a low price makes the plate rotor of even greater attraction to the designer than heretofore.

The development of the materials for the *end forgings*, may be regarded as a part of the development of solid forgings; although the problems in the shaft ends are not as accentuated as in one piece forgings, due to the relatively small size.

The *bolts* form one of the most vital elements of the plate rotor, and the selection of bolt material is of paramount importance.

The usual material up to a few years ago, was chrome-nickel steel, having a yield point of about 100,000 lb. per sq. in., an elongation of 20 per cent, and a 50 per cent reduction of area. This was superseded by a molybdenum-nickel steel, having somewhat higher yield point and reduction of area. The real virtues of the molybdenum-nickel alloy, however, have been attributed to the difference in Izod-impact test, which is almost twice as high for the molybdenum-nickel steel as for the chrome-nickel steel.

A similar material is used for the *coil retaining rings*, where the demands on stress are of the same order as those of the through bolts. A considerable amount of development has been carried out on the problem of obtaining satisfactory coil retaining rings of non-magnetic steel. Such steels are in use, but their chief objections are high cost and difficulty of machining.

*Problems Encountered in Building Plate Rotors: The Bolt Threads.* In most of the present four-pole rotors, the bolts have a diameter of 5 in. When it is remembered that these bolts carry a stress at the root of the threads of about 40,000 lb. per sq. in., and that this stress must be maintained indefinitely, it is evident that the design and the cutting of the threads call for more than ordinary care.

The question of stress concentration in the bolts is clearly of great importance, because the average stress must be maintained fairly high. As usual, in cases of ductile materials under steady stress, the existence of a certain stress concentration does not indicate failure when the maximum stress reaches the yield point, because the yielding itself causes a readjustment of the stress. In judging the merits of different types of threads, however, the factor of stress concentration is of sufficient importance to furnish a reliable aid in selecting the most favorable type.

Certain interesting results were obtained in 1925, by R. V. Baud, by photo-elastic measurements on various types of threads. The threads investigated were Whitworth (somewhat modified), Acme, and Buttress threads, (Fig. 22). Table II gives the results of these tests in terms of factors of stress concentration.

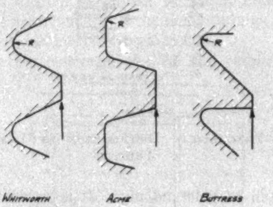

FIG. 22—TYPES OF THREAD

The models tested were made to a certain scale from the actual threads on a five-in. bolt with four threads per in. The factor of stress concentration expresses the ratio of the maximum stress obtained by the photo-elastic experiments to the average stress, calculated by ordinary beam formulas.

TABLE II

| Type of thread | Radius of fillet inches | Factor of stress concentration |
|---|---|---|
| Whitworth | 0.027 | 1.75 |
| Acme 1 | 0.003 | 2.65 |
| Acme 2 | 0.013 | 2.00 |
| Acme 3 | 0.023 | 1.75 |
| Acme 4 | 0.045 | 1.54 |
| Buttress | 0.023 | 2.46 |

This comparison gives very favorable results for the Acme type of thread with large fillets at the bottom, and this type has been adopted. The threads in use at present are 29 deg. Acme threads with a 0.023-in. fillet at the bottom.

There is another, and more important, source of stress concentration in the bolts, which has been investigated very thoroughly during the last two years. This concerns the distribution of the load on the different threads. It is evident that, due to the extension of the bolt and the compression of the nut, there will occur a certain difference in pitch, which will tend to throw a heavier load on the first threads in the nut. In bolts of ordinary size and moderate loads this question is relatively unimportant, but on large bolts under heavy load it may cause serious stress concentration in the bolt, near the first threads.

An analysis of this problem was made for the first time in 1925 by S. Timoshenko and J. P. Den Hartog; and it was found that if no yielding occurs the load distribution on the threads is very far from uniform. Fig. 23 shows the results that were obtained for a five-in. diameter bolt, cut with Acme threads, four threads per in. The length of the nut is seven in., and the threads are assumed to be cut with no clearances and equal pitch in bolt and nut. It is evident from this result that the major share of the load is carried by about six threads from the bottom of the nut.

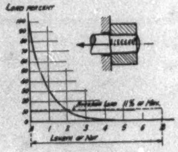

Fig. 23—Theoretical Distribution of Load on Bolt Threads

Several solutions have been advanced to eliminate this condition, among which may be mentioned cutting the threads to unequal pitch in bolt and nut, and arranging the nut in such a manner that the threaded portion is in tension. These solutions had to be discarded, however, since they demanded an accuracy in cutting the threads which could not be attained even with special precision tools.

Further study of the problem has shown, however, that the load concentration on the first threads is so high that yielding will occur. After this yielding has taken place, the load is transferred to additional threads, until the maximum load can be sustained. The load distribution is then of the type shown in Fig. 24. It was found that this yielding begins at about 60 per cent of the maximum load. The yielding is very minute however, and the actual displacements are of the order of machining inaccuracies.

The most important concrete result of this investigation was that it was shown unnecessary to have the nut longer than one-bolt diameter; in fact, where practical conditions so require, the nut may be made considerably shorter than one diameter of the bolt.

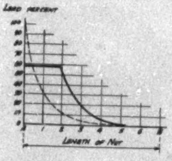

Fig. 24—Actual Distribution of Load on Bolt Threads

*The Problem of Assembly*. Before the assembly the plates and the shaft ends are machined, and the bolt holes drilled. The rotor plates are then stacked, and when the stacking is completed, the structure is held together by temporary bolts. The bolt holes are then reamed and the regular bolts inserted and tightened.

In the earlier rotors it was customary to tighten the nuts by a crane, and record the torque required by a scale beam on the crane. This method was found to give erratic results, due to variations in the finish and lubrication of the threads and seats of the nuts. This method was then superseded by determining the bolt stress, by the total elongation of each bolt, which proved to be quite satisfactory as far as final results were concerned. It was comparatively slow, however, and in certain cases considerable variations of the wrench pull, which could not be accounted for, were obtained.

For these reasons, a special pulling machine was developed by G. M. Eaton, whereby it is possible to stretch the bolts to their correct stress (and if necessary to a certain over stress) before the nuts are tightened up. The introduction of this equipment has proved to be a very valuable improvement, and the uniformity of the results is no less an advantage than the increased production.

The arrangement of this bolt puller is shown in Fig. 25. Two bolts, diametrically opposite, are pulled up at one time. The puller is attached to the end of the bolts, outside of the nuts, and when the load is raised to its specified value, the nuts can be run on by a small hand wrench. The actual stress in the bolts is checked by the elongation, after the puller is slackened up. The bolts are tightened in steps until the final load is reached. After machining, the rotor is again returned to the puller, and the bolts are subjected to a temporary over stretch, which is left on for a short time, after which the load is backed off to normal.

### DETAILS OF ROTOR CONSTRUCTION

In the present type of machines the maximum rating that can be obtained from certain core dimensions is limited by the heating of the rotor. There are two methods by which this limit can be raised. One is to provide more room for copper by deepening, or widening the slots, or by changing the insulation arrangement. Changes in slot dimensions, within the limits set by saturation of the rotor teeth, can be obtained only by the introduction of better rotor materials. The other is to improve the rotor ventilation. The developments of the last years have been concerned with both of these methods, but the most important change has been accomplished by improving the rotor ventilation.

The problem of rotor cooling is a most difficult one, because of the difficulty of studying the actual conditions with the rotor in motion. This problem is being investigated by the use of stationary and rotating models, and it is expected that the results of these investigations will throw further light on the rotor ventilation phenomena.

FIG. 25—BOLTS PULLER FOR TURBO-ROTOR BOLTS

One of the most important advantages of the plate construction lies in the possibility of obtaining radial ducts between the plates, communicating with the axial ducts. For this reason the rotors of Westinghouse generators have always been cooled by air circulated through the body. Fig. 26 shows the original arrangement of this system of rotor ventilation. The axial vent ducts are cut at the bottom of the slots, and communicate with the air gap through radial ducts, which are milled out of the rotor plates before assembly.

The introduction of rotor plates with a large central bore made possible a modification, which will increase the volume of air going through the rotor. Fig. 27 shows a cross-section through one of the rotors with the modified system of ventilation. Oblique holes are drilled in the shaft ends before they are assembled with the plates. These holes carry a part of the cooling air to the center of the rotor. The remainder is carried through axial holes through the teeth in the end portion of the rotor. Radial slots are cut down along each rotor tooth before the plates are assembled, and these slots serve to discharge the air from the center of the rotor. In this construction there is no change in direction of the air at high velocities and, therefore, the pressure drop is decreased. In the older design it was necessary to provide a steel cell in the slots to protect the mica lining where the coils were adjacent to the air ducts. In the improved construction, the steel cell can be omitted and the corresponding space made available for copper. With the plate construction it is thus possible to obtain a cooling system without resorting to drilling a number of radial holes in the teeth. The arrangement of the end windings has been subjected to considerable development.

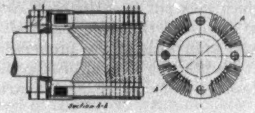

FIG. 26—ORIGINAL SYSTEM OF ROTOR VENTILATION

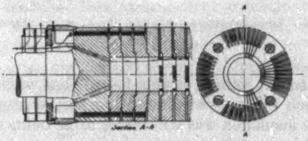

FIG. 27—MODIFIED SYSTEM OF ROTOR VENTILATION

In the earlier constructions the coil retaining ring, Fig. 28, was assembled on the end plate, at *A*, and on the rotor body, at *B*, with an ordinary iron-to-iron fit without shrink allowance. The end plate was usually put on the shaft, at *C*, with a slight press fit. The insulation under the retaining ring consisted of two layers of mica each 1/16 in. thick.

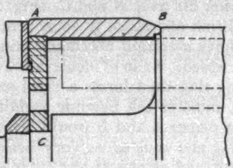

FIG. 28—ARRANGEMENT OF COIL RETAINING RING AND END PLATE

It is evident that this insulation has an unusually heavy duty to perform, being subjected to a continuous pressure of over 5000 lb. per sq. in., in certain cases; to a high temperature; and to frequent shearing action, due to expansion and contraction of the coils. In 1923, looking ahead to these larger units, a new insulation was developed, consisting of channels made of molded asbestos, which were put over the coils, and the retaining ring was lined with the same material. A series of tests was made to investigate the properties of the new insulation, by subjecting it to approximately the same cycles of pressure, temperature, and shearing action as in the actual rotor. It was found that while the old insulation broke down under 365 temperature cycles, the new insulation was still intact after being subjected to 1800 heat cycles.[8]

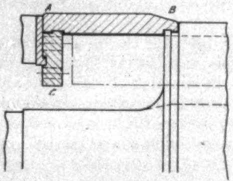

Fig. 29—Arrangement of Coil Retaining Ring and End Plate

As the size of the individual units increased, and it was necessary to raise the stress in the coil retaining ring, it was found that the expansion of the retaining ring under this stress amounted to as much as 0.050 in. on the larger units. Naturally, with this expansion the centering of the retaining ring was no longer adequate, and the eccentric displacements that were possible were great enough to affect the balance of the rotor to an appreciable extent.

The logical solution for this difficulty would be to provide shrink fits at *A B* and *C*, (Fig. 28); and determine the shrink allowance in such a manner that the fits would have a certain necessary minimum pressure at the over-speed. It is evident, however, that, since the retaining ring then forms a rigid extension to the rotor body, most of the bending rigidity of the rotor between the planes *A* and *B* would be provided by the retaining ring and thus cause very heavy reactions on the end plate, and on the fit at *C*. It was found that these reactions were great enough to disrupt the shrink fit at *B*, and cause the ring to work loose. In order to provide for this possibility, the fit at *A*, between the retaining ring and the end plate, has been made loose, with a clearance great enough to absorb the differential deflection of the rotor between the planes *A* and *B*. The end plate is shrunk on the shaft, and furnishes a rigid base for application of balance weights, and for attachment of the fan.

A further modification of this design is shown on Fig. 29, where the end plate has been left entirely clear of the shaft. Heavy shrink fits are provided at both *A* and *B*, and the fits are made with retaining flanges to prevent the ring from coming loose under the influence of centrifugal forces from heavy balance weights in the end plates. This construction is ideal, in that it completely eliminates the disturbances due to weaving of the retaining ring, and it furnishes an unobstructed passage for the air into the rotor.

It was thought at first that the practise of shrinking the retaining ring on the rotor and on the end plate would cause very large reactions on the fits at stand still. It is true that if the entire radial force of one of the large retaining rings had to be supported by the fits, the ring would probably fail due to shear. It is a fortunate incident, however, that the retaining ring assumes an hour-glass shape at stand still, so that the major part of the radial force is eliminated by contraction in the middle.

The curves in Fig. 30, illustrate this condition for the size of retaining rings used on 1800-rev. per min. machines. It is seen that if both ends of the ring are shrunk on a solid piece, the middle contracts about 80 per cent of the shrink allowance. On the smaller retaining rings for 3600-rev. per min. machines the middle actually contracts to a smaller diameter than that given by the unstressed state. When one end is shrunk on, only about half of the ring is affected. As a result of this, the reactions on the fits at stand still are actually about 25 per cent of the full radial force.

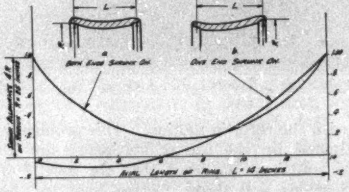

Fig. 30—Deformation of Shrunk-on Coil Retaining Ring at Stand Still

This condition produces another important advantage, in that it is possible to press on the rings cold, with reasonable press capacity; about 750 tons being sufficient for the largest rings made so far.

The problem of constructing internal fans has become increasingly difficult for the great amounts of air required for these rotors. A new type of fan with axially curved blades was developed by C. J. Fechheimer in which the bending stresses on the blades, caused by centrifugal forces, were modified into tensile and compressive stresses, (Fig. 31). With the use of this fan it is possible to equip 1800-rev. per min. machines of 75,000-kv-a. rating with internal fans.

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[8] "Trends in Turbine Generator Development," by F. D. Newbury, *Electric Journal*, July, 1927, p. 334.

## CRITICAL SPEEDS

*Earlier Conceptions and Design Limitations.* The problem of critical speeds in the rotor structure has played a peculiar role in the development of turbo generators; and its influence in placing limitations on the rotor dimensions represents a striking example of the fact that complete absence of theoretical analysis is sometimes to be preferred to unreserved faith in the results obtained by a faulty or partial analysis.

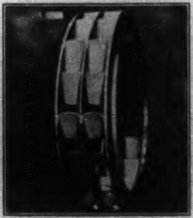

FIG. 31—NEW CONSTRUCTION OF INTERNAL BLOWER

In the early stages of the development it was generally considered impossible, or at least undesirable, to run the machine through any of its critical speeds, and the rotor proportions were definitely limited by the demand that the calculated critical speed must be well above the operating speed. The gradual enlargement of 3600-rev. per min. units soon made it necessary to readjust this conception, and De Laval's demonstrations of the self-centering properties of a flexible shaft furnished proof of the practicability of running through the critical speeds of the rotor without danger. This demonstration was made about 30 years ago, and the theoretical explanation of the phenomenon followed soon after; but it took considerable time before this idea was accepted by practical designers. Thus it is not more than about 15 years ago that the practise of designing 3600 and 3000 rev. per min. machines to run through the lowest critical speeds was firmly established.

At that time there was considerable hesitancy on the part of the designers to extend this reasoning to four- and six-pole designs, primarily because the demand for large units in these types was not yet sufficiently great. It is certain, however, that the old conceptions of the danger of critical speeds played an important role in retarding the natural expansion of the low speed units. When the demand for large units became sufficiently strong, this barrier was finally broken down, and about five years ago the Westinghouse E. and M. Co. no longer felt hampered in the extension of large units to sizes where it was necessary to run through the first critical speed.

*Influence of the Flexibility of the Bearing Supports.* As the numbers of units in active service increased, the troubles due to vibrations gradually began to form an appreciable portion of the expense of installing and bringing these large machines into satisfactory operation. A survey of these troubles brought about the surprising result that the large units, operating well above the first critical speed, generally caused less vibration troubles than the smaller units of a similar design, believed to operate below the first critical speed of the rotor. Vibration tests on a number of units of the latter type disclosed the fact that the first critical speed of the rotor, when mounted in its actual bearings, may be far below its calculated value. In certain cases the critical speed was found to be less than one-half the value predicted by calculations of the rotor, while in others it was found very near the operating speed.

The quantitative influence of flexibility of the bearing supports is most easily understood by considering the simplest case of a single concentrated mass on a flexible shaft in two supports. It is a well known fact that the critical speed of this arrangement corresponds to the natural frequency of lateral vibrations in one plane. Thus, if the shaft deflection under the influence of gravity is $y_1$, the critical speed, $N_c$, corresponds to the natural frequency in cycles per min. of a mathematical pendulum of length $y$, that is

$$N_c = \frac{60}{2\,n}\sqrt{\frac{g}{y}} = 187._7\sqrt{\frac{1}{y}} \text{ rev. per min.}$$

The stator deflection of the rotor has no other significance than that of being a measure of the flexibility of the shaft. The critical speed remains the same whether the shaft is rotated in the vertical or horizontal position, in fact it would remain unchanged if the intensity of the gravitational attraction were changed, or if it disappeared altogether.

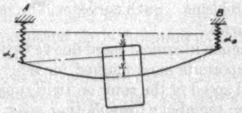

FIG. 32—SINGLE ROTOR SPAN IN TWO FLEXIBLE BEARINGS

As far as the natural frequency of vibration is concerned it is immaterial whether the elastic static deflection occurs in the shaft itself or in elastic members in its supports. We may thus consider the rotor deflection as made up of two components; $y_1$ due to the flexure of the shaft itself, and $y_2$ due to the flexure of the bearing supports (Fig. 32). The critical speed is then

$$N_c = 187._7\sqrt{\frac{1}{y_1 + y_2}} \text{ rev. per min.}$$

It is evident at once that this critical speed is lower than that obtained for the rotor in rigid supports; the reduction being dependent upon the relative magnitude of $y_1$ and $y_2$.

It is thus a fairly simple matter to obtain an approximate value of the critical speed when the bearing supports are flexible. The actual conditions of motion of the rotor body are quite complicated, however, and several aspects of the problem are not fully known. This applies particularly to the case when the bearing supports have different flexibilities in the horizontal and the vertical directions. The information available at the present time indicates that the natural frequencies in the direction of maximum and minimum flexibility give the critical speeds with sufficient accuracy. This result must be considered in the nature of an empirical result. Ordinarily, the maximum flexibility occurs in the horizontal direction. Thus, most two-bearing machines will be found to have two critical speeds, both somewhat below that calculated for the rotor in rigid supports. Fig. 33 shows the general speed-amplitude curve that is obtained from one of the bearing supports of an arrangement of this kind. Experimental curves of this nature form one of the most important means for scientific analysis of vibration problems. Such curves will be referred to as *resonance curves.*

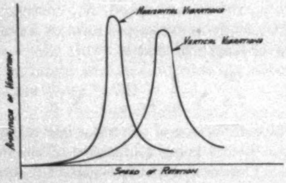

Fig. 33—General Type of Resonance Curves for Machines Operating in Flexible Bearings

The reduction in critical speed due to flexibility of the bearing supports is most marked for machines with a high critical speed of the rotor on rigid supports. It is evident from the above formula that, even if the shaft deflection $y_1$, could be reduced to zero, corresponding to an infinite value for the critical speed of the rotor in rigid bearings, the actual critical speed, now determined by $y_2$ alone, may still fall below the operating speed.

This is actually the case for most machines in the 1800-rev. per min. class, having a rotor weight over approximately 50,000 lb. With the most sturdy design of the bearing supports, which have been used so far, it has been found that the actual critical speed cannot be brought above about 1900 rev. per min., no matter how rigid the rotor structure. For rotors of this type, having a calculated critical speed of about 2400 rev. per min., the actual critical speed will usually fall around 1200 rev. per min. A similar situation exists with machines of the 3600-rev. per min. class, when the rotor weight exceeds about 5000 lb. Here the possible upper limit of the critical speed is about 3200 rev. per min.

Thus, while the designer may be able to control the rigidity of the rotor structure to a certain extent by changes in the rotor proportions, he is usually not able to influence the rigidity of the bearing supports to any appreciable extent. The natural limitations of the construction of the stationary parts, and the materials involved, prevent increases beyond certain limits. In addition, the oil film in the bearings provides a certain unavoidable flexibility. The available information on the subject of elasticity of oil films is very scant, but those investigations that have been made[9] indicate that the oil film can be considered as a mechanical spring interposed between the shaft and the bearing.

So far, the discussion has been restricted to the fundamental mode of motion of the rotor, and no reference has been made to the complications arising from the fact that most machines are operated in more than two bearings. The influence of the bearing flexibility upon the second critical speed of the rotor is similar to that of the first, but the lower limits of critical speeds are considerably higher. In the largest machines under construction at the present time the second critical speed of the rotor is of major importance, and it has been found that a reduction of about 30 per cent, from the value calculated for rigid bearings, must be considered. The conditions in multiple-bearing machines, with rigid couplings, are somewhat more complicated but the problem is susceptible of theoretical analysis, the only difficulty being in fixing values for the flexibility of the bearing supports.

It is evident from the above that critical speeds above the operating speed of 1800 rev. per min., as well as most 3600-rev. per min. machines, are practically impossible of realization; notwithstanding the fact that purchasers of electrical machines frequently include a clause of this nature in their specifications.

*The General Foundation Problem.* The flexibility of the bearing supports is only one of the factors that cause the great discrepancy between calculated and observed critical speeds. A fully satisfactory perspective of the situation is obtained only when the entire unit, with its foundation, is treated as one problem. It is here that the real limitations of mathematical analysis come to light, and the machine designer is made to feel the true importance of intuitive judgment and good luck.

In order to arrive at an understanding of the mechanics of the systems that are obtained when the entire machine, with its foundation, is treated as a unit, it is necessary to represent the system by a dynamical model, where the dynamically essential features are emphasized, and the non-essentials hidden. Such a dynamical model must be constructed separately for both the vertical and the horizontal directions, but the difference is usually only in the magnitude of the various system constants, and not in the arrangement.

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[9] Stodola, *Schweizerische Bauzeitung*, May 23, 1925. Hummel, *V. D. I.*, *Forchungs Arbeiten*, Heft 287.

Fig. 34 illustrates a typical layout of a foundation for an 1800-rev. per min. machine; and Fig. 35 represents its dynamical model.

It is unnecessary to point out that models of this type represent very rough approximations of the actual systems, and certain parts must be modified further before they yield practical results. A reasonably complete analysis can be made, however; the chief difficulty lies in the lack of knowledge of the system constants involved. It is worthy of note that even if complete mathematical analysis is not made, certain results of importance can be obtained by direct inspection of the dynamical models. As an example of this may be mentioned a condition which is obvious from inspection of the dynamical model shown in Fig. 35. It is evident that the amplitude of vibration of the bearing *A*, produced by a disturbance in the rotor mass $m_1$, depends to what extent the nearest stationary mass, $m_3$, is made to take a part of the motion. This reveals a relation which has not always been observed in the present foundation designs, namely, the necessity for effecting an intimate mechanical connection between the rotating and the stationary masses.

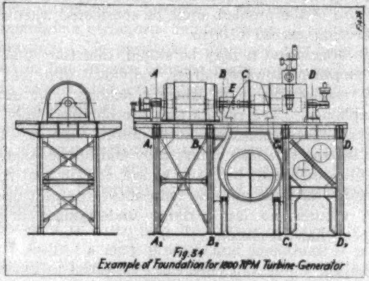

Fig. 34—Example of Foundation for 1800-Rev. per Min. Turbine Generator

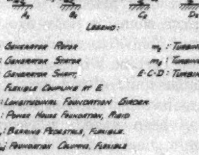
A
B
E
C
D
m₁
m₂
m₃
m₄
A₁
B₁
C₁
D₁
A₂
B₂
C₂
D₂
Legend:
m₁: Generator Rotor
m₂: Generator Stator
A-B-E: Generator Shaft, Flexible Coupling at E
m₃: Turbine Spindle
m₄: Turbine Cylinder
E-C-D: Turbine Shaft
A₁-B₁-C₁-D₁: Longitudinal Foundation Girder
A₂-B₂-C₂-D₂: Power House Foundation, Rigid
Bearing Pedestals, Flexible.
Foundation Columns, Flexible

Fig. 35—Dynamical Model for Four Bearing Turbine Generator and Foundation

Apart from the general considerations of this nature, however, successful operation always demands that no condition of resonance exist near the operating speed. The system shown in Fig. 35 has four distinct resonance frequencies for the vertical and horizontal directions, making a total of eight resonance peaks; of which some, may overlap and some may fall wholly outside the operating range. In machines of great lengths it may even be necessary to consider the rotational vibrations of the rotor and stator masses as well, thus increasing the number of resonance peaks further.

The term "critical speed" now assumes an entirely different significance from the ordinary conceptions of critical speeds in the rotor alone. The chief object of the analysis is to enable the machine to run in a hollow of the resonance curve; and there are, evidently, no simple rules that will accomplish this result.

It may be of interest to show some of the experimental results obtained from the actual installations which have furnished the justification for this treatment of the problem.

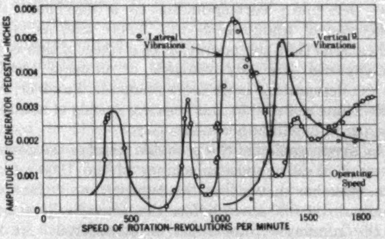

Fig. 36—Resonance Curves for Generator Pedestal of Four Bearing Turbine Generator Experimental Result Obtained from Arrangement shown in Fig. 34.

Fig. 36 shows the resonance curves that were obtained from a 25,000-kv-a. unit of the type shown in Fig. 34. These curves were obtained from the outboard pedestal of the generator end *A*. Each one of the peaks obtained on these curves could be accounted for, at least approximately, by analysis. The maximum peak for horizontal motion occurred at 1200 rev. per min. This was found to represent the fundamental critical speed of the rotor, which was calculated to 2380 rev. per min. for rigid bearings.

*Present Design Limitations.* Further progress is necessary before the designer of large turbine generators can take a definite stand with respect to the design limitations made necessary by critical speeds. At the present time two methods of approach are possible. One is to continue along the old channels of thought and discuss the problem in terms of critical speeds of the rotor, making such allowances for the foundation influence as experience will indicate. The other is to attack the foundation problem aggressively, and regard the rotor proportions with no greater emphasis than is demanded by its place in the foundation problem.

Whatever method adopted, it is evident that the old conceptions of placing limitations on rotor dimensions based on the critical speeds of the rotor alone, in rigid bearings, must be modified. The development of large units was needlessly hampered by the old conventions of critical speeds, and by adhering to these conventions, certain designs were actually made with erroneous rotor proportions. This applies to almost all of the larger machines designed to run below the first critical speed.

Apart from these considerations, however, there are certain problems which demand immediate attention. Probably the most important point at the present time is the question of what is the absolute lower limit to which the critical speed of a rotor can be brought without danger. At the present time, very few machines have been constructed with critical speeds below 900 rev. per min., corresponding to a maximum shaft deflection of about 0.045 in. There are, as yet, no indications that the operation of a rotor of this type is accompanied by any dangers or unusual troubles. As the demand for large units increases, however, rotor deflections of 0.100 in., and critical speeds of about 700 rev. per min. will be necessary.

An investigation of the probable trend of the development of Westinghouse machines of the 1800-rev. per min. class has shown that the capacity can be increased to about 120,000 kv-a. before the second critical speed of the generator rotor must be considered. At that capacity, the fundamental cirtical speed will be of the order of 700 rev. per min. It may be necessary to screen off certain core lengths on the present, maximum diameter between about 120,000 and 150,000 kv-a. but above this limit it is still theoretically possible to extend the rotor length and the capacity still further. How far this can be carried is entirely problematical.

It is believed, however, that the bending stress in the rotor might play an important role before the limit in critical speed and rotor deflection is reached. This bending stress is alternating, and, taking into consideration the probable conditions of stress concentration, and the fact that it exists in conjunction with certain other stresses, there will probably be considerable hesitancy on the part of the designers to raise this stress far above 5000 lb. per sq. in. with present rotor materials. This will limit the output to a value around 150,000 kv-a., but a considerable amount of further research is necessary before this figure can be established definitely.

In addition to this limit of the bending stress there are certain other features to be considered. Since no journals are absolutely uniform, and no rotor has an absolutely uniform deflection in all directions, it is evident that, as the rotor deflections are increased, the effects of these errors may also be increased. The danger from this source lies primarily in the danger of producing resonance with the second critical speed. It is not possible to place a limit on the rotor length from this consideration, but it is conceivable that much longer rotors than those built at the present time may give trouble on account of these causes.

The question of instability of the rotor in the air-gap will probably not be of consequence for any of the rotor lengths in sight at the present time. Unless the air-gaps are materially increased it is conceivable that this feature of the problem must be considered when shaft deflections exceed 0.100 in.

In conclusion it may be stated, therefore, that the development towards larger, individual units has not yet reached the point where a definite limit can be established. The results that are obtained when the units, under construction at the present time, have been put into service may conceivably add further elements to the discussion; but it is almost certain that if the demand for large units is maintained, the next decade will witness no less striking undertakings in this respect than the present.

## BALANCING AND VIBRATION PROBLEMS IN THE SHOP AND IN THE FIELD

Apart from the problems incidental to the building of the rotor body, its machining, the winding, and the assembly, the vibration problem figures very prominently in the process required to bring a machine into satisfactory operating conditions.

One of the primary requirements for smooth operation (apart from the question of design), is an accurate balance of the rotating parts. The Westinghouse Co. realized the importance of this process for large, high-speed machines at an early stage in the development, and its first balancing machine for this purpose was constructed more than 10 years ago. This machine had a capacity of 250,000 lb. and has been in continuous operation in the Turbine Works at South Philadelphia. In 1923 a similar unit, with a maximum capacity of 300,000 lb., was installed at East Pittsburgh. Similar equipment has been added, subsequently, for the 3600-rev. per min. machines. The construction of these machines, and the method of operation, is practically the same.[10]

With this balancing equipment the process of obtaining a practically perfect balance is a simple matter, but it has been found that the balancing process alone is not sufficient to insure smooth operation, except for the small units. Due to the mechanical imperfections of the coils, and their insulation, certain distortions of the rotor structure take place during the first hours of heating and rotation. It has been found necessary, therefore, to subject each rotor to a definite seasoning

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10. "Balancing Large Rotating Apparatus," L. C. Fletcher, *Electric Journal*, January 1924, p. 5.

process at full speed and maximum field temperature, and sometimes a stable condition is not obtained until after several days of seasoning. The rotor is heated by current through the field windings, and the seasoning is carried out in a special test rig arranged for this purpose. In order to maintain the field temperature sufficiently high it is usually necessary to enclose the rotor in a heater box, which is made of wood in order to eliminate heating by eddy currents. After a stationary state of balance is reached at full speed and maximum temperature, it is not unusual to find that the balance at room temperature and low speed is different. Ordinarily, however, a well seasoned rotor will maintain a permanent balance under all conditions of operation. No particular difference has been observed in this respect between plate rotors and solid rotors, some of the latter type having been very slow to become stabilized.

Even with the utmost care in these preparations of the rotor, the manufacturer is never completely guarded against troubles in the field, so that field balancing is a very important element of turbine-generator installation.

The cause of these field troubles is occasionally an actual slip in the shop process, and sometimes it may be traced to incorrect alinement; but in the majority of cases the troubles can be traced to unduly sensitive foundations. It is very seldom that a fundamental reconstruction of the foundation can be made, however, and the universal cure (which generally succeeds in eliminating the trouble) is to effect greater precision in the rotor balance by hand-balancing. These field troubles are always a source of inconvenience to the customer, and of unexpected expense to the manufacturer, but they have had one concrete result of importance, in that it is through these field troubles that the available knowledge of the properties of foundations has been gained.

Hand-balancing has always been regarded as more or less of a mystery, the secrets of which have been available only to a select few. The development of the art during recent years has dispelled a considerable portion of this attitude, however, and the systematic methods in use at the present time invariably yield quick results, provided that a cure is obtainable through balancing alone.

It is in this connection that the application of vibration instruments has been particularly valuable. In ordinary cases of balancing it is merely a question of measuring the amplitude of the vibration with a certain degree of accuracy. The vibrometer developed by the Westinghouse Co., has proved to be eminently useful in this respect. For more elaborate measurements of the vibration the Geiger Vibrograph made by Lehmann and Michells in Germany, has been used extensively. This instrument has the advantage of giving a graphical record of the motion, whereby the form of the displacement is also obtained. It is particularly useful in obtaining resonance curves, continuous records of amplitude and frequency, and the results shown in Fig. 36 were obtained by this instrument.

Many vibration problems encountered in the field are due to local conditions of resonance in bearing pedestals, frames, piping, flooring, etc. While the ultimate cause of these vibrations resides in disturbances from the rotor, it is very rarely that a cure can be effected by correcting the cause itself. The most effective cure is usually to change the natural frequency of the element in question, by stiffening or weakening. These local vibrations are not infrequently classed as serious vibrations of the machine as a whole, and a great deal of field trouble can be eliminated by particular care in the design of these parts.

Axial vibrations of bearing pedestals form a very important part of this item. The causes for these axial vibrations are not fully known, and there are cases on record where resonance has definitely been demonstrated not to be the cause. In many cases a cure has been effected by balancing of the rotor, although there is no apparent reason why unbalance should cause axial disturbances. It is probably safe to state that more than 30 per cent of field troubles are due to axial vibrations of bearing pedestals. This represents one example of the many practical vibration phenomena which are not yet fully understood.

Another group of unexplained phenomena has been observed in the vibrations of the steam turbines. Several cases are on record where the amplitude of a certain point would vary periodically with periods of several minutes or even hours. These phenomena are undoubtedly connected in some manner with temperature distortions, and they have been eliminated in several instances by modifying the supports of the turbine housing, but the actual causes are as yet hidden.

The question of alinement is a very important one for large turbine generators. This problem is complicated by the movements in the foundation that take place because of variation in temperature, particularly in cases of exposed steel foundations. Where solid couplings are used, the present practise is to aline the machine in such a manner that no flexural moments are introduced in the coupling, except those produced by gravity. Corrections are then made for thermal expansion. This method of alinement is sometimes modified when flexible couplings are used, but it is probably a safe procedure to aline flexible couplings fully as accurately as solid couplings.

## CONCLUSION

From the above it will be evident that the design of large turbine generators is one of extreme complexity, where practically all branches of engineering and science find their application. Now, as in the past, the designer of turbine generators is forced to work very close to the limits determined by available knowledge; and in many innovations, his only guide is the experience gained on artificial models, arranged to test out his theoretical investigations.

A program of development, such as described, is the result of the combined activities of the entire organization of a large company. For many of the results recorded in the paper we are indebted, among others, to C. M. Laffoon, G. M. Eaton, E. Mattman, W. J. Merten, S. Timoshenko, G. M. Lessells, and C. F. Hill, members of the research, metallurgical, and design departments of the Westinghouse Co.

## Bibliography

The following bibliography covers a few of the outstanding papers on the subject of turbine generators up to the present time:

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E. Roth, TRANS. A. I. E. E., Vol. 44, 1925, p. 905, *Three-Phase, 60,000-kv-a. Turbo Alternator for Gennevilliers.*

F. D. Newbury, *Electric Journal*, July 1927, p. 334, "Trends in Turbine Generator Development."

Robert Pohl, 2 *T. Z.*, Feb. 2, 1927, "Neuzeitliche Turbogeneratoren und Luftkuhler."

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## Discussion

**W. J. Foster:** I want first to say a word about the voltage. Mr. Henderson takes the position with which I think we will all agree that we do not want any higher voltage in generators than we can well get along with, on account of the space taken up by the insulation, the temperature drop through the insulation, and so forth, and yet at the same time, as pointed out by Mr. Henderson in his paper when he speaks about the amperes per slot and their deleterious effect on losses and so forth, we need the higher voltage to keep the amperes down. We must balance up one effect against another.

There has been pressure brought to bear when we go above 13,800 volts to go to 22,000 or 23,000, since that is considered a standard voltage on transformers and in distribution. A number of intermediate steps has been made such as 18,000, 16,500. We had the 18,000 several years ago on engine-driven generators. The step to 22,000 volts on certain turbine generators was taken by reason of the pressure brought to bear on the manufacturers to go to that voltage on account of the great savings in bus construction, switches, and station wiring. It was found practicable to design the generators for that voltage.

I wish here to make just a little correction in the paper. I think Mr. Henderson and Mr. Soderberg spoke of only one plant where this high voltage is going to be introduced in a generator. There are two such plants. The generator for the first one has already been shipped. It will be installed before the more conspicuous one, which is the 208,000-kw. unit, is installed. The latter consists of three 22,000-volt 85 per cent power-factor generators, 1800 rev. per min., the larger or high-pressure unit 89,411 kv-a. and the smaller ones identical in size, 72,941 kv-a. each. It has been found in developing the insulation and in testing the same that results have been obtained that are quite reassuring. We now have confidence that the 22,000-volt generator is all right.

With reference to the matter of insulation, I am interested in what has been said and what is shown in the paper with regard to the use of shellac, inasmuch as that conforms with my own experience. There are other bonding materials that are far preferable, especially in what happens when they are subjected to higher temperatures.

In the matter of corona discharge, that is another reason why we hesitate to wind for very high voltages. It might be brought forward as a reason why we should hesitate at such a voltage as 22,000. I was especially interested in what the authors have said regarding the development of a covering that arrests or prevents any serious deterioration due to the discharge. I trust that what has been discovered is going to prove permanent. Many years ago in connection with some of the first high-tension generators that were installed at high altitudes where trouble developed due to corona, it appeared desirable to devise a corona-protecting sheathing. The problem was attacked at the factory, and a certain pigment was discovered with which the finished coils were painted, and apparently a cure had been obtained. It was a cure, but only temporary. That protection soon wore away and disappeared. Later the practise became established on the part of the manufacturers with whom I have been associated of putting on a metallic sheathing, which consisted of a metallic ribbon insulated on one side and wound around the fully insulated coil. That was very effective, but in time it was liable to wear out.

I am still of the opinion that the problem is a very important one and should be solved to everyone's satisfaction. I hope what the authors describe will prove the real solution. Whatever corona-protecting sheathing is used must be of such nature as to adhere perfectly to the surface of the completely insulated coil and be a substance that will not deteriorate due to temperature or chemical actions that may take place. As many know, asbestos sheathing offers a solution in many cases.

With regard to hydrogen, the authors point out some of the advantages. I simply wish to add that undoubtedly the benefits obtained by hydrogen are greater on the rotor than on the stator, and as a result it strengthens the weaker part of the generator. It has long been recognized that the rotor is the limiting feature.

What is shown in the paper in regard to the skeleton-frame stator construction is of special interest to me, as the group of men with whom I am associated devised similar stator frames as much as two years ago. In fact, several machines have been built, including the first of the 100,000 kv-a., which I presume at the present time is on its way to the Pacific Coast. That has been a great step forward, for the reasons pointed out in the paper.

**B. A. Behrend:** The paper is divided into parts dealing with the electrical problems, the ventilation problems, the mechanical design of stator and rotor, and the dynamical balance of the latter. I shall use for this discussion the same headings as those used by the authors in their paper.

### II. VENTILATION

The multiple-radial system of ventilation, the principle of which is the invention of Parsons and Holcombe, has been carefully studied and developed and its adoption by the Westinghouse Company marks a step of great progress. We thus see the axial system of ventilation abandoned and supplanted by one whose efficacy has been thoroughly demonstrated. The inherent limitations of the axial system resulted in higher temperatures for the stator coils which entailed both serious electrical and mechanical difficulties. Moreover, we are now no longer confronted with the making of a decision as to the possible superiority of one system of ventilation over another as the principal makers of large turbine units are now using substantially the same system. This marks progress when it is the result of steady evolution and improvement.

The mode of ventilation is naturally connected with the medium of ventilation and the authors have referred to the use of hydrogen gas for cooling. It is my opinion that, given the necessary time to convert the power-plant owners, hydrogen will be freely used on large units raising efficiencies, reducing size, and making possible higher voltages on the individual unit. Water and oil cooling of stators, extensively used abroad, appears to have found little or no favor here. A. B. Field's discussion bears on this subject.

### III

In the design of stator coils, sound principles as laid down by A. B. Field, R. E. Gilman, W. H. Taylor, W. V. Lyon, and noted foreign designers, have been adopted. This necessitates cross-overs in the slots which, as Mr. Henderson states, have enabled him to hold down eddy-current losses to about 30 per cent of the corresponding d-c. loss. The method used by Henderson, shown in Fig. 4, appears to be a good mechanical design. With this type of construction, however, care has to be exercised to prevent establishing paths for eddy currents which could be induced by the external field.

The important researches on temperature conditions in stator coils carried on for years by F. D. Newbury and his associates, should have come in for a general review. This was the kind of work which led up to sound principles of design of stator coils and ventilation and was fundamental in character.

Some little time ago (TRANSACTIONS, A. I. E. E., March 22, 1907) I described a 100-kw. 22,000-volt generator which had then been in operation continuously for some time. I said that "where individual units of very large capacity are installed in power plants, a potential of 20,000 volts is feasible and it is to be recommended in units of 10,000 kw. and above." Today, twenty years later, it might be advisable to weigh these words and to raise the generator voltage with all the advantages which the handling of smaller currents brings. It is right here where hydrogen cooling will be useful in connection with the increased generator voltages. He is a bold man who will predict the limit of capacity of turbo generators, but I am willing to go on record here that this limit lies between 150,000 kw. and 200,000 kw. Twenty years ago (*Cassier's Magazine*, May, 1907) I urged 25,000-kw. units at 22,000 volts as unit sizes for power-generating stations and, having seen this prediction realized and to some extent exceeded, I now go on record stating that we are reaching the technical and economic limit at eight or ten times this size, *viz.*, at 200,000 kw. or 250,000 kw. at the most.

### IV. GENERAL DESIGN

Here it is interesting to note, first, the adoption of a 4 per cent silicon steel for the core punchings. The enormous advantage in reducing the core loss to one-half of what it would be with ordinary iron is obvious.

The heating of the finger plates is not a new phenomenon. It has had to be met before by the adoption of non-magnetic finger plates, made of brass or bronze. Losses in the finger plates are two-fold, first, those due to induction from the armature, second, those due to induction from the revolving field. In the earlier machines with weak armatures and powerful fields the heating was due principally to the latter; in the present types with powerful armatures and weak fields, the heating is primarily due to the ampere-conductors per slot. It is obvious that a considerable flux must pass through the finger plates with slots twice as deep as they used to be. This flux is roughly proportional to the product of the depth of the slot into the current density. The better the cooling, the greater the latter. Hence the loss in the finger plates, which is proportional to the square of the induction, is easily ten times what it used to be in the older machines. It is, therefore, necessary to study the magnetic circuit of the finger plates carefully so as not to give an opportunity to set up eddy currents. Excessive heating of the finger plates is a source of danger as their mechanical strength is reduced by high temperatures, leading to the possibility of fracture. Thus broken pieces may drop into the air gap and damage the insulation of the coils. The strength of aluminum alloys is generally affected by heat and their use is, therefore, to be avoided for parts liable to be the seat of eddy currents.

The question of generator stability is brought up by the authors. I have elsewhere (Chicago Regional Convention, Nov. 1927) discussed this matter and I wish to emphasize here that I hope that the designers of large generators will not return to their former practise of using strong fields and weak armatures in order to raise the frequency of natural oscillation of the generators. We have gone through all this in the past and it would be painful to see it all gone through again.

### V. STATOR CONSTRUCTION

The adoption of welded structural-steel frames for turbo generator stators is highly to be commended. Cast iron is unsuited for this purpose, and cast steel is too costly.

### VI. MECHANICAL CONSTRUCTION OF THE ROTOR BODY

As referred to by the authors, I developed the radial slot construction and the plate rotor for the Westinghouse Company about nineteen years ago. The reasons for abandoning steel castings or forgings were those given by the authors. The bolted shaft ends, first used by DeLaval on his single wheels in his steam turbines, were used by me in 1907 on the first of thirteen generators of 300 rev. per min. for Niagara Falls (TRANSACTIONS, A. I. E. E., 1908, p. 811). The first machine of this series was destroyed on its overspeed test on April 28, 1908. A complete description of the accident with copious illustrations was given by me before a joint meeting of the American Societies of Civil and Mechanical Engineers and of the American Institute of Electrical Engineers, in Boston, fifteen years ago. The type of rotor construction is shown in Fig. 5, in the writer's paper already cited. An 8-in. unpierced central disk of 3½ per cent nickel-steel supported two nickel-steel end rings forged like tires on a mandrel. Careful specifications accompanied the order for these forgings.

The fractures revealed a high axial combined with a low radial ductility. The elastic limit of the radial test bars was high and so was their ultimate strength. The central disk had evidently not suffered at all; it remained intact and test bars taken from it showed no signs of excessive stress. The use of bolted-on shaft ends proved entirely successful, thus indicating the way to the bolted ends with unpierced shaftless rotors described by the authors and introduced by Behrend and Field.

Different committees investigating the accident at the time arrived at the conclusion, which was buttressed by tests of models made in a Tinius Olsen testing machine, that, had the forgings possessed proper ductility in a radial direction, there would have been no reason to have expected the accident. In replacing these machines I used on the first one 2-in. rolled carbon-steel plates, and on the second one, 2-in. rolled nickel-steel plates, carbon steel having proved too delicate in its heat treatment. These plates were all quenched in water. Particular attention was paid to uniformity of ductility in two directions at right angles to each other, *i. e.*, in the direction of rolling and at right angles thereto. Samples taken from the plates in these directions has to bend cold flat 180 deg. without showing cracks. (See TRANSACTIONS, A. I. E. E., 1918, p. 886.) It is this type of construction of which thirteen units have been in continuous operation for twenty years at Niagara Falls and these are the first 2-in. plate rotor types ever built.

The enormous advantage of such a plate construction was irresistibly impressed upon my collaborator A. B. Field and myself and when we joined the Westinghouse Company in 1909, we introduced this type for turbo rotor construction, returning to the unpierced plates but retaining the 2-in. plates of rolled material.

In my paper before this Institute of 1908, I had given a complete stress chart showing both the radial and tangential stresses in revolving disks, both pierced and unpierced. This chart is given in Fig. 2, herewith, and it has been reproduced by Professor Stodola in his book on steam turbines and by C. M. Laffoon in an able paper before the A. S. M. E., 1922, p. 485, Fig. 12. The important point here is the sudden doubling of the tangential stress when the disk is pierced at the center. In disks made of materials of low ductility, with unequal radial and tangential stresses, the tangential stress may easily treble as a direct result of a central hole. We, therefore, avoided such piercing and developed the design shown by the authors in their Fig. 14.

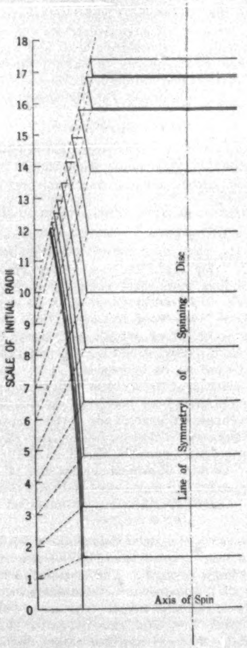

Fig. 1—Deformation and Strain Chart of Rapidly Spinning Disk and Toroid

From the above numbers 1, 2, 3, to 10 indicate initial inside and outside radii of disk before deformation. These points by virture of the strain distribution travel along the dotted lines according as the inside radius of the toroid is small or large. The disk or toroids develop concave surfaces as boundaries perpendicular to the axis of spin.

The theory makes the cylindrical boundary generated by a line parallel to the axis of rotation, while in reality the generating line is a curve with its center on the line of symmetry making a convex surface for the disk.

Had the accident to the Niagara Falls generator, described in my paper of 1908, been the only one of its kind, or had such an accident occurred only in a machine of my design manufactured in a certain plant, the evolution of a new type might have seemed unnecessary. But in 1922, two generators with cast-steel rotors of twice the rating of our machine of 1908, designed by other engineers and built by another company, were totally destroyed at Niagara Falls. Thus I have felt warranted in urging the Westinghouse Company unceasingly to adopt a type of construction which uses neither castings nor forgings and which permits easy discovery of flaws and defects of material although entailing increased cost of machining.

Now four conditions appeared to me paramount in the design of the plate rotor:

1—The use of a commercial material which could be looked over and inspected in "small bits", so to speak, at the shops of the generator builder.

2—The possibility of using unpierced disks in which the radial and tangential stresses equal each other at the center.

3—Great ease of effective rotor ventilation.

4—Avoiding excessive tangential stresses on the inside of the bored hole due to shrinking fits on the shaft.

Against these advantages must be cited the greater cost of machining.

Now the authors appear to favor forged rings instead of plates and thus they lose the advantages cited under (1) and (2). In forgings of 8-in. thickness with a central hole the maximum stress is liable to be about twice the stress in the 2-in. unpierced disks or plates. The probability of an invisible flaw remaining undiscovered is 1/4; 1/4 = 1/16 or 16 times as great in an 8-in. forging than in a 2-in. plate, assuming the same probability of occurrence of flaws in either material which is hardly the case. In general, let us assume a forged or solid steel rotor of 100-in. length and let us compare with the same a plate rotor of equal length with plates of 2-in. thickness, then the probability of a flaw remaining undetected is 2500 times greater in the first than in the second case. This is, perhaps, the most graphic way of bringing home the issue between solid rotors, cast or forged, and plate rotors of the type proposed by us. Of the latter, the Westinghouse Company has built considerably over one hundred large units which have been entirely successful.

Forging rings on a mandrel has a tendency to lower the radial ductility on account of the direction of the forging work and, simultaneously, to raise the axial ductility, which is useless; the process of mandrel forging thus operates in the inverse direction to that which is desirable. This statement is made in spite of the micro-photographs shown by the authors in Fig. 20. The tendency toward such variation can be offset only by extensive heat treatment, counteracting the effect of the forging work, and such heat treatment is not in the hands of the builder of the generators.

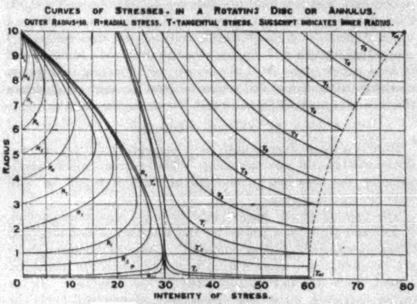

Fig. 2

With rolled plates it is possible to order material for stock in large quantities and at times when the steel mills are not busy on standard specifications; with the rolled or forged rings this cannot be done and every job is a special job. We secured plates from the armor plate department of the Carnegie Steel Company at Munhall, Pennsylvania, of nickel steel with properties which showed that an elastic limit of 55,000 lb., an ultimate of 75,000 lb., and 28 per cent elongation with 45 per cent reduction was obtainable, thus indicating that it can be done. It is, of course, undesirable business for the mills as it is fastidious work.

## VIII. Critical Speeds

In his splendid analysis of critical speeds, Mr. Soderberg points out the importance of operating at a speed between the first and second critical speeds or between the fundamental lateral vibration and its first harmonic. He shows the effect of the oil film in the bearings as resulting in a lower critical speed than that which would obtain were the bearings perfectly rigid and he concludes that "it is here that the real limitations of mathematical analysis come to light and the machine designer is made to feel the true importance of intuitive judgment and good luck."

Mathematical analysis cannot solve the intricate problem of dynamic balance but such analysis as Mr. Soderberg has given elsewhere of systems of several degrees of freedom supplies a great and useful guide for which the engineer will be duly grateful to the author.

**Edouard Roth:** I wish to add to the very suggestive list of great units which have been built or which are under construction in the States, a unit of 40,000 kv-a. at 3000 rev. per min., 13,500 volts, built by the Société Alsacienne de Constructions Mécaniques at Belfort (France) which is, as far as I know, the largest unit at 3000 rev. per min. and of which I append some photographs (Figs. 3 to 5). Fig. 4 shows how the very important question of shipment has been solved; this is a problem on which the authors rightly insist very much. The solution of this problem is easier for the American designers, first because the railway clearances are larger in America than in Europe, and then because the American railway companies allow for a heavier load per axle, than the European companies; for example, in Europe there exists no car that can carry 275,000 lb. The kind of construction represented in Fig. 5 allowed us to build up the sheet-iron core in the factory, but the winding had to be put in place at the power station. The solution by means of a skeleton frame is very ingenious but I do not believe that it can be generally employed in Europe.

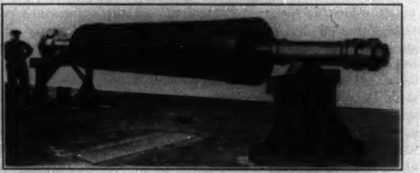

Fig. 3

In the case of the machines built by the Société Alsacienne, it is not easy to use this kind of frame on account of the ventilation system. In my paper, which is referred to by the authors, I gave a detailed description of this system, the advantages of which were so clearly emphasized in the discussion by Mr. Fechheimer. This system has proved to be very efficient and is used by my firm for all turbo alternators.

In this same paper I explained in detail that this system of ventilation is possible owing to the leakage slots, which were so thoroughly discussed on the same occasion. I repeat that these slots make it possible to build alternators with a flux which assures great stability (another problem on which the authors insist) and which at the same time gives a very small instantaneous short-circuit current. These leakage slots are used by my firm for all turbo-alternators of outputs above 5000 kv-a.

Another problem which the authors mention is that of the heating of the finger plates, supporting the stator teeth, which is due to stray load losses; may I add that there are also losses in the end plates and in the extreme portions of the lamination of the stator core. In my opinion, which is also that of the authors, the only and best remedy is the use of non-magnetic steel for the wedge and end plates, as well as for the retaining rings of the rotor.

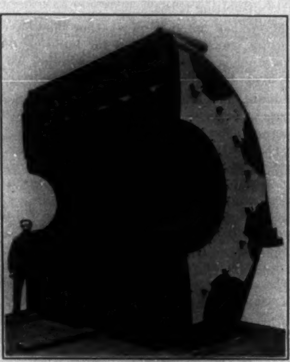

Fig. 4

Fig. 5

The problem of the suppression of eddy currents in the bars has found a perfect solution in the use of the special bars of which a detailed description was given in my paper.

The swelling and wrinkling of the insulating tubes has also been for us an object of research, and I agree entirely with all that the authors say on this subject. I might add that it is obvious that the manufacture of the tubes is the first condition of success and that the quality of the raw material, which is the mica folium, is also very important, not only as to the kind of bond used, but also in respect to the constitution of the material itself. The mica folium must be thin and of a very regular thickness; it must be flexible, very homogeneous, and the quantity of bonds used must be *very small*. These properties can be given to the material only by a strictly mechanical manufacturing process, excluding any manual intervention; it is only in this way that perfect homogeneity can be assured. A material of this kind is produced quite automatically by a very ingenious machine, built by a manufacturer of insulating materials in France; this machine needs no other manual operation than that which is absolutely necessary for its general handling.

The problem of the elimination of corona was solved by us many years ago, in exactly the same manner as that given by the authors, namely by the application of a semi-conductive coating on the insulating tubes.

I should like to ask the authors whether they have ever found trouble in using transformer plates for building up the stator core, as this steel is very brittle, and whether an increase in radius of the fillets has given a complete remedy to these troubles.

I will not dilate upon the mechanical construction of the rotors. Up to the present time, we have always used, for four-pole rotors, the construction which is described in my paper; on a shaft, grooved to permit the entrance of the cooling air, are placed forged disks, with clearances between them, forming vents. This construction will still be used for a 75,000-kv-a. alternator, of 65 per cent power factor, 1500 rev. per min., which is now being designed. I may add that this alternator will be built very liberally, and would be capable, with normal heating, of an output of 90,000 kv-a.

The rotors for 3000 rev. per min., are made of solid steel forgings. The study which the authors make of the different stresses that may occur in rotors is very interesting. I understand very well that the problems which present themselves to American engineers on this subject are very difficult on account of the great length of the rotor; this is not only due to the large outputs of the machines, but also to the fact that the speed is 1800 rev. per min., and not 1500 as in Europe.

The critical speed of our 3000 rev. per min. machines is always under the normal speed. Up to the present this was not the case for the 1500 rev. per min. alternators, for which it is above the normal speed. For the alternator mentioned above, it will, however, be above the normal speed.

**A. B. Field:** One is perhaps disappointed that among references to so many investigations one finds no signs that the possibilities of an oil-immersed stator have received consideration or been investigated. We hear of the increased size having necessitated higher voltages, and of the difficulties thereby encountered; but, even so, do we reach a voltage which is really reasonable for the output? Emphatically not, at 22,000 volts. We hear of the huge volumes of cooling air to be handled; of the windage loss which seems to be leading to hydrogen cooling with all its complications, granted that the danger scare is largely a bogey, and so on.

Oil immersion is no recent suggestion. No doubt most designers and users have in a casual way considered its possibilities during the past 25 years. Its possibility first really appealed when bakelite-paper products had proved their worth, and the production of a thick insulating tube of mechanical construction suitable as a separator between rotor and stator came within the realm of practical polities, somewhat less than 20 years ago. In reviving the suggestion then, one realized that, even if it were practicable, the construction could not be justified by the requirements at that date. The position has been different for a good half-dozen years now, and the matter calls for a sufficient expenditure to determine definitely whether the difficulties and disadvantages justify a continuance of the cold shoulder. With a bakelite-paper tube between stator and rotor the rotor can be water, oil, or possibly steam cooled, and run in a partial vacuum, eliminating windage loss. The stator can be oil-cooled by a confined forced circulation, not the kind of casual circulation which a transformer puts up with. For a given temperature rise of the cooling medium the flow of oil across unit area of cross-section of the duct at say 300 ft. per min. deals with about 130 times as many watts as the flow of air at 4000 ft. per min. Thus, end-to-end axial ducting becomes practicable, or end-to-center; if desired, the cooling medium can be given direct access to the bare copper, or to metal walls almost in contact with such. The voltage limitations are pushed away to a figure with which we need not quarrel at the moment. The possibilities and difficulties of oil immersion cannot be determined without expenditure on an adequate scale; if the matter has not been investigated within the last 5 years or so, a serious study is due.

**W. J. Merten:** I want to point out in more detail two outstanding metallurgical developments included here and of great importance to the design engineer.

One is the full exploitation of the potential physical characteristics of plain carbon steel in the disk forgings described, by a selective heat treatment for uniform grain refinement, allowing thereby very much higher working stresses without a reduction of the factory of safety.

The second is the development of a new type of steel for retainer rings and bolts with properties not as yet equaled in any of the alloy steels which have been tried for this service. The nickel-molybdenum steel and its composition has been mentioned in this paper.

1. The problem of producing a high-strength disk was worked out from a standpoint of securing complete and uniform distribution of structural components, diffusion of metalloids, and complete destruction of segregation by the employment of high temperatures after the forging operations were completed, and before reheating for grain refinement and quenching which was then followed by strain-relieving thermal treatments. The successful and uniform structural refinement of large massive sections of steel forgings by high-temperature treatment has been described in a paper[1] before the A. S. S. T. September, 1927, at their Detroit Convention. Since then, a more complete refinement by quenching and tempering has been introduced, with corresponding increase in physical properties. This step to make use of the steel to the safe limit of its capacity is not surprising at all and a natural consequence of more complete knowledge of the potential properties of steel and its response to thermal treatments. It will be noted that advantage has also been taken of all the mass reduction that the design engineer would permit by hollow forging so as to facilitate the greatest possible rate of heat abstraction during quenching.

The microphotograph of the etched steel shows a sorbitic structure in which a combination of high elastic properties with a satisfactory degree of ductility can generally be assured.

In concluding this part of the discussion, I should like to state that I believe the exploitation of the inherent properties of carbon steels by thermal treatment for this class of service has been carried to the limit of safety and any further increase in stresses in rotor service must be met by judicious selection of alloy steels or adjustment of crystal structure by mechanical working.

2. The second metallurgical development—that of a new type of steel for retainer rings and bolts, is of even greater importance, since it indicates the direction towards successful alloy-steel application in parts of fairly large sections and actually obtains a corresponding return in physical values for the additional cost of the alloys.

The working stresses in rings and bolts are of a magnitude which exclude the low-percentage alloyed steels from receiving consideration. The 1 per cent chrome 3 per cent nickel-steel has been favored for this service. Every now and then, however, the inherent difficulties from temper brittleness as well as its sluggishness and resistance to complete structural refinement during forging and heat treatment and its tendency to develop hair cracks during heat treatment and probably during rough machining makes it a rather questionable material for a basis of composition for still greater performance. Experiments with modified percentage compositions of chrome and nickel confirmed this conclusion.

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[1] "High-Temperature Treatment of Castings and Forgings as Evidenced by Core Drill Tests from Heavy Sections," by W. J. Merten, *A. S. S. T. Transactions*, January, 1928.

The molybdenum-nickel alloy steel for this application resulted from cooperative studies and experiments with the staff of the Molybdenum Corporation of America and the Midvale Steel Company and has consistently given on retainer rings an elastic limit of 95,000 lb. minimum with a yield point of 115,000, ultimate tensile of 130,000 and reduction of area of 55 per cent.

A 6-in. diameter, 16-ft.-long forged bolt showed 90,000 lb. elastic limit and equal values of ductility. The impact izod values of this steel are over twice those of the chrome-nickel type. While this characteristic may not add to the usefulness of this alloy in rotor service, I have always associated good or high impact values with a decidedly amplified crystal-recovery tendency when such steel is subjected to alternating stresses of great magnitude, suggesting good cold-working properties and possibilities to improve their physical characteristics thereby.

**R. B. Williamson:** The problem of ventilation in large turbo generators has been so well worked out that, for the present at least, the size of these machines is not limited by this feature. Also by the use of transposed stator conductors the difficulties due to eddy currents have been overcome. So far, therefore, as stators are concerned, the limit as to size and output may be very large because stators can, if necessary, be shipped in parts and built up and wound in the station.

The real limit as to the output of these large turbo generators lies in the rotor which must be shipped complete, as it is hardly practicable to ship one of these large rotors in parts and wind and balance it at the station.

Another limit lies in the materials available for the construction of the rotor. The paper illustrates a very interesting method of sectionalized construction whereby the use of very large forgings is avoided. However, it will be noted that even with this construction, quite large and massive forgings are required for the end shafts. These must have material in them of high grade as they are of the same diameter as the central disks and subjected to similar stresses.

Steel makers have made great progress in the last few years in the production of reliable forgings of large weight and dimensions. What the designer has most to fear is the presence of hair-line cracks in such forgings. A heavy forging may show excellent physical characteristics, yet if any cracks are present these may spread and cause failure. The danger of cracks is much reduced if the forging is made from an ingot that has not been allowed to cool. In other words, the forging should be made by the steel maker, and from the time the steel is poured until the forging is finished, the process should be continuous so that the steel is not subjected to the strains of cooling and reheating. All rotor forgings should be bored for inspection.

However, the main body of the rotor is only one item; suitable material for the coil-retaining rings is just as important. Failures have occurred in these rings; at least two cases having come under my observation. These were both due to cracks starting at one edge and working their way across the ring until it finally failed. Coil-retaining rings for turbo generators are generally made of alloy steel in order to secure the necessary tensile strength. Such alloy steels, if tempered too hard, are liable to develop cracks. While a relatively high tensile strength may look well, because it shows a high factor of safety as compared with the working stress, it is in fact more dangerous than a lower tensile strength combined with more ductility. Some years ago, the writer specified 100,000 lb. per sq. in. as the yield point for this material with an elongation of 16 per cent. This was later changed to a maximum of 85,000 lb. yield point with 22 per cent elongation. Also special precautions were taken in the machining of the end rings to secure smooth surfaces, free from tool marks and scratches that might start cracks, by carefully finishing and polishing all corners and fillets.

**Robert Pohl:** It may be of interest to American designers to compare the views and experience of a promiment European company, the Allgemeine Elektricitäts Gesellschaft. The points raised are, however, so numerous that I can only briefly touch upon some of them. The prevalence of 50-cycle systems and other causes have had the effect to direct the development in Europe chiefly upon two-pole (3000 rev. per min.) machines. These are constructed for far bigger outputs than the two-pole machines in the United States. The largest 3000 rev. per min. generator in operation is a 40,000 kv-a. A. E. G. unit. Even bigger outputs are at present contemplated. Four-polar designs are correspondingly less frequent. While they have been worked out up to 100,000 kv-a. at 1500 rev. per min. there has as yet been no chance here of building four-pole machines above 50,000 kv-a. Six-pole turbo alternators at 1000 rev. per min. have altogether ceased to play any part. The largest units of this type, unique at the time of their construction, were the 62,500 kv-a. A. E. G. machines of the Goldenberg Station, designed in 1916. Their system of ventilation is multiple radial, similar to Fig. 1 of the paper, with this difference, that the radial ducts are alternately inlet and outlet passages so that even more complete uniformity of ventilation over the whole active length was obtained. We find it advantageous, however, to let the air from the back pass from the inlet to the outlet ducts through axial holes in the core immediately above the winding and to cool the rotor exclusively with air passed through it and over its surface from either end of the rotor. Much depends, in this connection, on whether the stator or the rotor is the limiting member from the temperature point of view. The scheme of rotor ventilation of the A. E. G. rotor allows a greater quantity of air to pass through its vent ducts, and that is a particularly effective way. The typical A. E. G. rotor design—laminated teeth inserted in a solid core, with form-wound coils, baked, insulated, and assembled before assembly of the teeth—I suppose to be known. It may not be appreciated, however, that, like the Westinghouse plate rotor, it greatly simplifies the forging question, since the forged core has only about 70 per cent of the diameter and half the weight of a solid rotor forging. It also permits of very effective coil ventilation since the air can be made to pass axially along the copper through passages between teeth and coils. We found this direct cooling of the copper about three times as effective as indirect cooling.

The Westinghouse plate rotor design evoked great interest when it was discussed in London some twelve years ago. The investigation and development of its mechanics as disclosed in the paper, form perhaps its most interesting part. Perhaps the authors could add some further information as to the tests to make sure that the bolts are free from flaws and residual strain. Can they be tested by Röentgen rays?

While large two-pole forgings require special precaution, we find less difficulty over here in getting reliable forgings for four-pole machines of drum design with separate shaft ends, where the drum can be forged on a mandrel. We employ high-grade alloy steel, twice heated, quenched in oil at different temperatures and annealed. We test the finished forging for flaws by heating as well as by electro-magnetic methods. Test specimens are taken axially, tangentially, and radially. Apart from yield point, elongation and contraction of area, importance is attached to the span from yield point to ultimate strength and to the micro-photograph, but particularly to the impact test. For the latter, we employ not the Izod but the Mesnager specimen. Unfortunately, different impact tests are not comparable and it is to be hoped that some international agreement on the details of impact tests will be reached before long.

With regard to the mechanical factor of safety, the formula

$\frac{1}{n} = \frac{1}{n_s} + \frac{1}{n_v}$ appears to me somewhat arbitrary, especially considering that the alternating bending stress in the rotor is independent of the speed while the centrifugal stresses increase with the square of the speed. A more practical conception of the safety of a rotor would, I think, be conveyed by stating the overspeed at which ultimately failure will occur. The endurance limit, by the way, is not defined in the paper. Some define it as the amplitude of reversing stress which the material will stand indefinitely, others for 10,000,000 reversals. Again the method of test may be of importance. We employ high-frequency load variations, 500 periods per sec., so that an endurance test up to 10,000,000 reversals can be carried out in less than 3 hrs.

The bending stress does not appear to us, however, to play an important part. In our largest rotors, it only amounts to 3.5 per cent of the tangential stress at the 30 per cent overspeed. Of course, it will become much bigger in four-pole rotors when the critical speed of the shaft is dropped below the running speed.

Coming to the question of the critical speed, our experience does not confirm the observation that it actually occurs below the running speed even where it was meant to be above. On the contrary, we always find it in close agreement with the calculated values for the shafts alone. I suppose the difference is explained by our different practise in building machine foundations. While in the United States steel structures are usual, we invariably employ heavy concrete foundations together with rather heavy bedplates. So we feel justified in adhering to the old conception that the running speed is definitely either below or above the running speed. I may mention that our 100,000-kv-a., 1500 rev. per min. design still belongs to the former class, the large two-pole rotors to the latter.

Another difference, not of experience, but of opinion, concerns the generator voltage to be chosen. While the authors favor raising it as high as 22,000 volts for large sizes, I prefer to keep to 6600 volts as far as possible and to form a working unit of generator and step-up transformer, the latter placed near the generator and joined to it through copper bars without any intermediate switch gear. We thus gain an extraordinarily high degree of electrical safety together with a high space factor for the slot area, the necessary reactance without leakage slots or the like, and practical freedom from transients. Corona precautions can be dispensed with. By raising the potential of the neutral point, we obtain a simple and comprehensive protective system. This generator-transformer layout at 6600 volts was adapted for the 62,500-kv-a. Goldenberg machines and recently for the 90,000-kv-a. machines of the Klingenberg Station. It can be used for the largest units now contemplated without raising the voltage above 13,000 volts. It is very likely the cheapest, as well as the safest system wherever step-up transformers have to be employed in any case.

**J. A. Kuyser:** (communicated after adjournment) Concurrent with the development of large 1500 and 1800 rev. per min. sets in the U. S. A. has been the development of 3000 rev. per min. generators in Europe, culminating in alternators of 50,000 kv-a. 3000 rev. per min. which are now put forward commercially.

Several of the problems touched on by the authors have been encountered by other designers and different solutions have been proposed.

The problem of the relative movement of the coil-retaining rings and the rotor body arose on some 18,000-kv-a. 3000 rev. per min. Metropolitan Vickers alternators built about 8 years ago which were at that time the largest alternators at that speed in existence. In its most severe form the movement results in pieces breaking off the tip of the steel retaining ring and in breakage and open circuits in the top turns of the rotor winding. In a less severe form it is observed on smaller sets and causes powdering and disintegration of the mica insulation, and severe rust formation on the ring and rotor body due to the hammering at the spigot end.

The method adopted by the M. V. Company to overcome this trouble is illustrated in the accompanying Fig. 6 which is almost self-explanatory. A sleeve concentric with the shaft is provided either in one piece with the rotor body or bolted or shrunk into position. The rotor shaft ends are free to move inside this sleeve without communicating any movement to the rotor end plates and the coil-retaining rings. In practise all relative movement at the spigot is completely eliminated without the necessity of having heavy pressfits at this point.

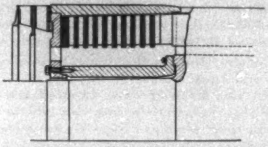

FIG. 6

With reference to the transposed slot conductor shown in Fig. 4 of the paper and the combination with transpositions at the coil ends, we have used this winding with highly satisfactory results for the past 12 years.

With regard to the question of stator insulation considerable speculation has arisen on the swelling of the stator slot insulation into the radial air ducts. A very obvious method of preventing this difficulty is illustrated in Fig. 7 herewith. In this construction the wall of the slot is continued across the air duct by metal spacers and a continuous slot is obtained presenting a smooth surface to the coil.

The authors emphasize the difficulties of obtaining large forgings having adequate elongation. In this connection it seems that the view taken is rather pessimistic. We have obtained many forgings up to 60 tons in weight having guaranteed properties as follows:

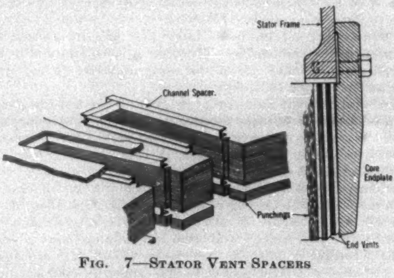

FIG. 7—STATOR VENT SPACERS

Ultimate tensile strength 80,000 lb. per sq. in.

Yield point 46,000 lb.; elongation, 20 per cent; radial, 24 per cent, tangential 24 per cent longitudinal.

The properties on a test piece taken from a core trepanned out of the center of these forgings are on an average: ultimate tensile strength, 75,000 to 80,000; yield point, 40,000 to 50,000; elongation, 17-20 per cent, although the makers do not give guarantees on the latter figures. These properties are very satisfactory for annealed forgings of such large dimensions.

The authors make some interesting remarks on the question of stability. Hitherto in discussions concerning stability the system characteristics have generally been neglected; as pointed out the percentage lighting load is of importance, but of great importance also is the amount of synchronous load on the system, since this load will contribute leading kv-a. in case of a voltage drop and tend to counteract the drop. Another point of importance is the magnitude of the load fluctuations and the rapidity of the load increase. We are now using in some cases a small permanent-magnet generator driven at about 800 rev. per min. from the governor shaft to supply current to the field system of the main exciter. By means of this system and a voltage regulator considerably greater stability can be obtained than that corresponding to constant excitation.

In case of a unit being suddenly tripped by the Merz Price gear it is doubtful whether a short-circuit ratio of 0.9 will be sufficient to ensure that the load will be picked up by the remaining sets if the faulty unit is large compared to the remaining units.

The difference with European practise as regards short-circuit ratio is not as great as the authors state. Large 3000 rev. per min. generators are generally designed for a ratio of 0.65; the lowest ratio used is 0.6.

**G. A. Juhlin:** (communicated after adjournment) The lines of development given by the authors are in general the same as those which European engineers have pursued. The conclusions to be drawn, it seems to me, must also be those we have arrived at, namely, that the limiting factors in design of large units are no longer electrical but mechanical ones.

The introduction of the multi-inlet ventilating system would enable the designer to increase the length of his machines almost indefinitely, were it not for the fact that other limitations, such as deflection of the rotor, mechanical stress in the shaft, etc., prevent him from increasing the length beyond certain limits.

In connection with the ventilation scheme shown by the authors, it is of interest to note that the whole air volume required is provided by fans mounted on the rotor.

In Great Britain separately driven fans only are used by some manufacturers, or a combination of small fans mounted on the rotor which deal with a portion of the total air volume required, the amount depending on the length of the machines and a separately driven fan supplying the rest of the air.

Higher efficiency can be obtained from separately driven fans than from fans mounted direct, especially when dealing with large 3000-rev. per min. units.

For such units it would be necessary to adopt large-diameter rotors in order to provide sufficient inlet area for the fans. Such designs are undesirable from the point of view of mechanical stresses which become very high.

The windage losses increase very rapidly with the diameter with consequent reduction in efficiency of the unit. The efforts of British engineers have therefore been directed towards keeping the rotor diameters as small as possible, hence the use of the separately driven fan. In some recent machines complete turbo blowers have been mounted and driven direct from the alternator shaft.

Trouble with swelling of the stator-bar insulation was experienced as far back as 1916, and was diagnosed as being due to the solvent in the bond used in building the mica folium. This difficulty was reduced to a negligible amount by steam-curing the mica wrap after it had been applied by the wrapping machines.

Another problem which arose due to the necessity of subdividing the stator conductor into a large number of small strands was the difficulty of preventing looseness between the individual strands after prolonged operation.

Mica tape was used as insulation and after some years operation it was found that the individual strands were loose due to the bond having lost some of its adhesive properties. This difficulty was overcome by using very thin asbestos tape and treating the whole bar with a synthetic gum.

By this means a perfectly solid bar was obtained—uninfluenced by temperature as the gum used had to be treated at a much higher temperature than the copper would reach in operation, thus ensuring that the bar remained solid under operating conditions. Considerable credit is due to the manufacturer of this asbestos tape for producing a tape thin enough to enable us to employ it without losing too much space in the slot.

Non-magnetic finger plates and end plates have been used by British manufacturers for some years with good results. Better results still have been obtained by the use of copper end-plates having slots at the inner periphery corresponding to the stator slots.

The details of construction of the built-up plate rotor which the authors have given are extremely interesting. To have successfully overcome the difficulties mentioned in the paper is no mean achievement and reflects great credit on the engineers who have carried out the work. The construction is daring in conception and has proved itself sound in operation over a number of years. We in Europe are fortunate in being able to obtain large solid forgings with much better physical properties than those described in the paper.

I agree with the authors in their statements regarding the fundamental basis for the working stresses. It would seem, however, that the statement should be qualified to take care of special materials such as heat-treated nickel-chrome steels where the yield point and ultimate tensile strength are very close to each other. For such materials we have adopted a factor of safety on the mean of the yield point and the ultimate strength of the materials equal to the mean factor of safety of ordinary steels. With reference to tests and inspection of solid rotor forgings it has for many years been standard practise of the company with which I am associated, to insist on longitudinal, radial, and tangential tests on all our solid forgings.

All rotors above 25 in. in diameter have a hole bored through the center and a very stringent examination of the bore by means of a telescope and mirrors is made. If there is any doubt as to the soundness a special magnetic test is applied. In addition to this, sulphur prints are taken on the external surfaces for detection of segregations.

The authors' discussion on "Critical Speeds" is a very valuable addition to our knowledge on this important subject.

The influence of the flexibility of bearing supports and foundations is of special interest. Personally I have not come across any case where the critical speed of the set was influenced by the foundations, but this is undoubtedly due to the fact that all our machines are mounted on reinforced concrete foundations which, of course, are exceedingly stiff. Bearings are mounted in pedestals having low center and are therefore also very stiff.

I agree with the authors as to the necessity of the rotor winding being seasoned until stability is obtained and in this connection I would suggest that the baking and pressing of the coils before wedging is of great importance.

I also agree with the authors as to the necessity of balancing after a set has been put into operation no matter how carefully it has been balanced in the works. Minute changes in the rotor winding as well as in the alinement are bound to occur and must be corrected by re-balance in the field.

**P. L. Alger:** (communicated after adjournment) The authors have presented a most interesting and comprehensive survey of turbine-generator design, which strikingly exhibits the complexity of the modern designer's task. Their remarks in regard to armature coil insulation seem to me particularly significant of the progress being made. They state that the cause of insulation swelling and increase of dielectric loss with temperature is the boiling off of the alcohol in the shellac bond of the mica, and illustrate the point by Fig. 6, which shows a more than five-fold increase of insulation temperature rise when the ambient temperature is raised from 60 to 100 deg. cent. This idea was suggested in a discussion[2] of Professor Whitehead's article on Gaseous Ionization before the Institute in 1924.

All experience indicates that the black-asphalt-base insulating varnishes have superior characteristics to the yellow materials at elevated temperatures. The former retain their flexibility after prolonged heating, while shellac becomes brittle under like conditions. If the black bond described by the authors does not give off vapor when heated, and so does not swell, it will undoubtedly retain its flexibility also, and so will be suitable for use in external mica insulation on the end windings, as well as in the slots.

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[2] A. I. E. E. TRANSACTIONS, 1924, p. 124.

*Gaseous Ionization* before the Institute in 1924.

Practise in regard to insulation of turbine-generator end windings has always varied greatly, some companies abroad using hardly any end insulation at all; others, like the authors, using different kinds of insulation on the ends and on the slots; and still others using the same insulation around the entire coil. Which practise is best may always remain a moot question, but I believe that such papers as the present are of great value in bringing our ideas into better accord.

**S. L. Henderson:** I think Mr. Foster may have left an impression that I am sure he did not mean to leave, and that was that we really did not have any satisfactory means for preventing corona. He was simply talking about the permanency of this film. We have tested the film for many hours' operation at 30,000 volts to ground, in open air, and there has been no deterioration of the film, so that at least for that type of protection we feel that it has a permanent value.

Mr. Roth asked one question as to the brittleness of the transformer grade of iron which is used in the stator punching. We have been using silicon steel in turbo-generators for over five years, and there has been no indication of any teeth failing through the vibration. We feel that, of course, with silicon steel the question of stress concentration is of more importance than it is in the old rolled annealed steel, but we have increased radii at the bottom corners of the slot to such an extent that we feel certain there is no danger from the amount of vibration that can occur in a stator.

We certainly do owe a note of apology to Mr. Field for not having mentioned the question of oil insulation on the stator. However, it is a problem that we have not actively attacked; consequently, we could not add anything to this information that was already out of the problem. It certainly is not one that is going to be passed over. It is of interest in the high-voltage machines, and it has occurred to us many times in the last two years during the period that we were considering high voltages. After all, oil insulation would be a solution of many difficulties of high-voltage stators.

There are many mechanical difficulties in applying oil to the stator. It is necessary to devise some means of keeping the oil from the rotor; otherwise, the friction would be enormous. Consequently, we must find some barrier that will contain the oil around the stator that will be tight and mechanically strong, and that is rather a big problem.

**C. R. Soderberg:** Referring to Mr. Behrend's discussion, I should like to point out that his descriptions of rotor explosions show very clearly the need of scientific analysis of the stresses in the rotor structure. The fact that a manufacturer of machines of this kind has been fortunate enough to avoid failures for a considerable period of time certainly is very comfortable, but I wish to point out that it is dangerous to assume that this is a conclusive evidence of infallible design and construction methods. The problem of failures always involves an element of chance, and the designer who has been consistently fortunate may be next in turn.

The change in our rotor-plate material has proceeded through two steps. The start of the development was made on account of certain more or less unsatisfactory properties of the stock material to which Mr. Behrend referred. It was not as uniform as might be desired, and it was impossible to raise the strength above a certain limit. The first step consisted in forging the plates from a cylindrical ingot and rolling it in a tire mill. By this method we obtained a plate without a hole in the center with considerable improvement in elastic properties, as compared to the old material. If I remember correctly, the maximum yield point, which we could obtain with satisfactory ductility, was between 40,000 and 50,000 lb. per sq. in., as compared to about 35,000 lb. per sq. in. in the old material. The material described in our paper was then developed, and here it was possible to obtain outstanding strength and ductility.

As pointed out by Mr. Merten, the only method of utilizing carbon steels is by improvement in the heat treatment. Fully satisfactory heat treatment is possible only with a shape of the disks which admits of a uniform temperature diffusion. Thus, the hole in the center is necessary in order to raise the elastic properties and the ductility of the material. Of course, it is quite true that the stress in the center is increased by cutting the hole, but the existence of a certain stress is not in itself objectionable if its magnitude is known with certainty, and if it can be controlled to correspond to the properties of the material. The advantage of the solid disk, having a stress at the center, which is theoretically one-half of that in a pierced disk, appears to me somewhat doubtful. If the uncertainty of the material at the center of a solid disk, and the risk of microscopic cracks, are taken into account, it would seem that the disk with a central hole is preferable.

Referring to the discussion by Mr. Roth, I should like to mention that non-magnetic materials for retaining rings have been under consideration. Such materials are in use and appear satisfactory from the designers' point of view except for the fact that they are very difficult to machine.

Referring to the discussion by Mr. Field I wish to repeat the statement made by Mr. Henderson, that the authors very deeply regret the omission of the oil-cooled stator. The possibilities of oil cooling are obvious, but the difficulties of the mechanical design certainly appear formidable in comparison with those encountered with hydrogen cooling. I wish to point out, however, that the opinion of a man of Mr. Field's experience should receive due consideration, and it may be that when the problem is studied somewhat more closely, these difficulties may be found less discouraging.

Mr. Merten's discussion contained a reference to microphotographs. The microphotographs in our paper, more than anything else show the great improvement in the grain structure of the rotor material that we are now using, as compared with the old materials.

I think that Mr. Williamson's point on the question of unexpected cracks or weaknesses is very well taken. If we had complete knowledge of the failures that have occurred, I believe we would find that their occurrence very rarely can be attributed to too high values of the calculated stresses, but nearly always to unexpected faults in the materials.

Mr. Williamson's remarks on retaining rings is also very important. There is a very natural tendency on the part of the designers to raise the strength (the yield point) of the material at a sacrifice of ductility. While the theoretical value of the factor of safety may be increased, we may actually obtain a structure which is less safe than one having a material of a lower yield point. At the same time I wish to point out that in the retaining-ring material in use at the present time by the Westinghouse Company, and by other manufacturers, the ductility is actually superior to that of previous materials having a lower yield point. Thus, we have improved both the strength and the ductility and this is, of course, a logical procedure.

Referring, finally, to the discussion of Dr. Pohl, I wish to add a few remarks on the formula for actual factor of safety in cases of variable stresses, which was given in our paper. This formula is arbitrary only in the sense that the somewhat erratic experimental results available on this subject have been interpreted in a manner giving, in some cases, a slight amount of added safety. I refer to the replacement of the Gerber parabola by a straight line, joining the endurance limit and the yield point. An explanatory footnote on this formula will be given in further publication of the paper. The endurance limit is considered as the limiting amplitude of reversing stress, which can be applied in straight tension and compression an infinite number of times without failure. The available investigations on this subject seem to indicate that, for steels, there is no difference in the endurance limit when the number of reversals considered is greater than $10 \times 10^6$.

# Design and Application of Two-Pole
## Synchronous Motors

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***Synopsis.***—*The paper presents a brief résumé of the problems encountered in the design of two-pole high-speed synchronous motors together with a description of how they are met. A satisfactory design is worked out. The theory of the starting winding is given briefly in non-mathematical language, and curves are presented showing the results obtained in so far as current and torque are concerned. It also outlines the applications in which these motors have been used, pointing out both the advantages and the limitations of synchronous motors. This is followed by a description of the operating characteristics and of the method of controlling the motors.*

### INTRODUCTION

When there came a demand for large 3600-rev. per min. synchronous motors, it was apparent that it emanated chiefly from manufacturers of centrifugal compressors. In this application high speed is essential in keeping down the number of stages and the weight in the compressor. Steam turbine drives are used to some extent, and on the smaller sizes, induction motors have been used. The steam turbines are very satisfactory where a suitable supply of cheap steam is available, but frequently the source of steam is too remote. In most cases, 60-cycle electric power is readily available.

It was natural, in designing the high-speed synchronous motors, to turn to the already existing two-pole turbine alternators, which have specially designed features to make them suitable for high speed operation. The essential mechanical features of this type of generator are determined by the high centrifugal stresses involved, which make a small diameter imperative for the rotating elements. In order to get the required volume of iron into the rotating element, it is thus necessary to use a relatively long machine. This makes a long shaft necessary, and, when the rotor is of laminated construction, the shaft cannot be of large diameter on account of the stress at the bore in the punchings. With this in mind, the designer must obtain a proper balance between the unit stresses in the various rotating parts, at the same time maintaining sufficient stiffness in the shaft to insure smooth operation. The electrical requirements are to maintain a proper balance between the various flux densities and current densities, so that heating within the guarantees will be assured, and to obtain as high an efficiency as is compatible with reasonable cost. The various compromises thus utilized are to a considerable extent matters of experience.

It can readily be seen that a large part of the problem had already been solved by using the existing high-speed turbine alternators as a starting point. The available turbine alternators were of the type which had laminations for the rotating elements pressed on a steel shaft. These laminations had radial slots in which the polar field windings were wound, and these in turn were held in place in the core portion by metal retaining wedges placed in suitable wedge slots just above the polar windings. The polar windings were held in place on the end portions by steel retaining rings. By employing these special structural features, coupled with appropriate starting windings and changes in the electrical design, synchronous motors can be made having starting characteristics comparable with those of induction motors.

Although the two-pole synchronous motors are usually built for operation at unity power factor, a few have been built for operation at leading power factor. The design of motors for 0.9 or 0.8 power factor rating does not involve difficulties because the construction of the amortisseur winding leaves sufficient space in the rotor slots for a field winding of adequate capacity.

The problem of designing suitable starting windings for two-pole synchronous motors is much more difficult than in the case of squirrel-cage induction motors, principally because the short-circuiting rings must not in any way interfere with the polar field windings. Various schemes were proposed; one consisted of making two crown rings of bronze or copper slotted from continuous cylinders, then passing these over the polar windings and uniting the ends by a special brazing process or by electric welding. Another scheme for the starting winding was to insert bars of bronze or hard copper as slot wedges above the polar windings and properly connect these to low-resistance end rings consisting of annular plates just outside the end portions of the polar winding. The first scheme was impractical, due to the great difficulty of making a successful joint in the middle of the field core. It made the repair of the polar windings impossible, except by destroying the starting winding, and, finally, it occupied valuable space needed for the polar windings. The second scheme was actually tried out successfully. But in this case, also, the starting windings occupied some of the space required for the polar windings, and, while the joints with the short-circuiting rings were simpler,

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they were difficult and expensive to make. The plan finally adopted was to utilize the space at the thick ends of the teeth between the rotor slots. In carrying out this scheme the teeth are sufficiently cut away, as shown in Fig. 1, to provide room for two thin but deep conductors at the sides of the slots. Each of these flat conductors is folded over and joined outside the core ends to a flat copper or bronze disk which constitutes a very satisfactory end ring. Not only are two of these flat conductors employed in each winding slot, but extra slots are provided in the polar section, thus making the starting winding continuous about the entire periphery of the rotor; a condition difficult to obtain on a salient pole machine. In assembling this form of starting winding, the ends of the flat bars are temporarily held in the end plate by screws, and then the joints are perfected by a very carefully made junction of silver solder which has a melting point of approximately 660 deg. C. This arrangement of bars and end rings, in conjunction with the specially arranged wedges, provides an excellent starting winding. Since the bars are inserted in the field core before the insulated polar winding is assembled, the latter can be repaired at any time without disturbing the former. Proceeding along these lines, it was found possible to get enough copper into the starting winding to give a d-c. resistance of approximately one-half of 1 per cent. The starting winding is shown in Fig. 2, which indicates clearly how the winding is connected to the end rings. Fig. 3 shows the field windings and the starting winding assembled in the rotor without the steel retaining rings.

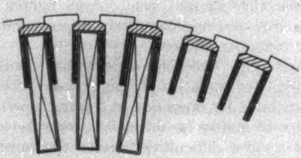

Fig. 1—Arrangement of Polar Winding, Starting Winding and Wedges in Rotor of Two-Pole Synchronous Motor

The first two two-pole 3600-rev. per min. motors, built with this form of starting winding, were rated 2550 hp., and were installed in a plant in the Andes Mountains at an elevation of 14,000 ft.

## THEORY

It is not within the scope of this paper to develop a mathematical theory of the starting characteristics. Such a theory has been worked out and will be briefly described in non-mathematical terms. Curves of torque and current calculated by means of this theory have been found to check approximately with the test curves.

Referring again to Fig. 1, it will be seen that the squirrel-cage bars are relatively deep. With this construction, the effect of the leakage flux at 60 cycles is to cause an uneven distribution of current density, concentrating it at the top of the slot. This causes an increase in the effective resistance of the bar, and a decrease in the reactance. This effect can be calculated by well-known methods applied to rectangular bars in rectangular slots with open tops.[1,2,3] For these motors, it was found that the effective resistance of the bars at 60 cycles was approximately twice their d-c. resistance.

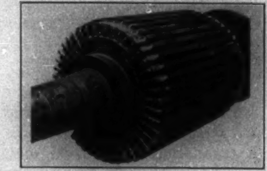

Fig. 2—View of Unwound Rotor of Two-Pole, 3600-Rev. per Min. Synchronous Motor, Showing Construction of Starting Winding

We come now to consideration of a particularly interesting feature of the starting winding. It was considered necessary to make the retaining wedges above the polar winding of short sections, each section being insulated from the other. This was necessary to prevent currents from flowing axially along the rotor. Such currents might cause dangerous burning unless proper connections were provided at the ends of the rotor to confine them, and it is difficult to do this without interfering with the accessibility of the polar windings. However, even though these wedges consist of short sections insulated one from another, they still possess the essential features of a dead conductor placed above a current carrying conductor in a slot. That is, the leakage flux from the starting winding can induce a voltage in the wedges which will cause a current to flow axially along the top of the wedge and return along the bottom, a complete circuit taking place in each wedge section. Theories of this action have been worked out by various authors.[2] It was found advisable to employ two kinds of wedges, some being of steel and some of an extruded metal. Various effects have been obtained by using alternately steel

Fig. 3—Completely Wound Synchronous Motor Field before Retaining Rings are Shrunk On

and non-magnetic wedges in different proportions. By thus varying the proportions of the two materials, different effective resistances and reactances can be obtained. The effect of a steel wedge above the starting winding is to increase the reactance by providing a path of lower permeance for the leakage flux; and to increase the resistance by contributing a heat loss caused by the eddy currents induced in the wedge by the leakage flux. The action is like that of a tertiary winding in a transformer, except that saturation is present in the wedge-leakage paths to a large degree and modifies the results considerably.

The method of calculation is to ascribe the additional resistance and reactance to the starting winding, although the flux causing the additional reactance cuts the wedge, and the resistance loss actually takes place in the wedge. By thus fictitiously placing the reactance and resistance in the starting windings, the motor starting characteristics can be calculated in the usual way with little difficulty. The start of the calculation is made by assuming a current in the starting winding. This determines the m. m. f. in the leakage paths and thus determines their degree of saturation. When this is known, it is easy to calculate by known methods[2] the leakage flux and get the effective resistance and reactance of the starting winding caused by the wedge. The effective resistance of the starting winding itself, due to its own non-uniform current distribution, can be determined in the usual way. The effect of the end ring is usually small but it may be included and thus the total effective resistance and reactance of the rotor for that particular frequency and applied voltage may be determined. Using these, the current which would flow in the starting winding is found. If it does not check with the value assumed, it is necessary to make a new assumption and repeat the process until a sufficiently close check is obtained. Points for different voltages and frequencies must be obtained separately because the constants depend on both. Thus the torque is not necessarily proportional to the square of the applied voltage, nor is the current necessarily proportional to the applied voltage.

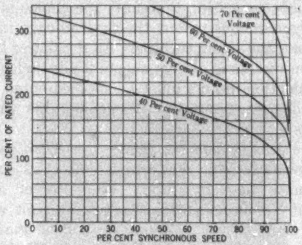

Fig. 4—Armature Current-Speed Characteristics of Two-Pole Synchronous Motor at Various Voltages

## Starting Characteristic Curves

Torque and current curves which were taken by test on a 1500-hp. 3600-rev. per min. motor, are found in Figs. 4-5 for different applied voltages. These curves clearly show how the current and torque vary with voltage and speed. It will be noted that the torque is maintained up to a point very close to the synchronous speed. The slope of the torque curves, from this point to synchronism, is very great and a measurement of the slope near synchronism indicates that the d-c. rotor resistance is about one-half of 1 per cent, as calculated. The fact that the torque is maintained to a speed so close to synchronism makes it comparatively easy to synchronize the motor. A consideration of the theory, described above, indicates that these torque and current curves could be changed materially by changing the proportions of steel and non-magnetic material in the slot wedges. Calculations indicate that at standstill the rotor resistance and reactance are each of the order of ten times the value calculated for direct current flowing in the starting winding. This shows how greatly the characteristics depend on the retaining wedges during the first part of the starting cycle.

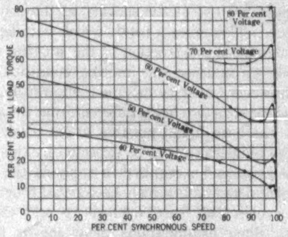

Fig. 5—Torque-Speed Characteristics of Two-Pole Synchronous Motor at Various Voltages

## Heating

When a synchronous or induction motor is started by means of a squirrel-cage winding from zero speed to synchronous speed, it may be readily proved that the heat generated in the rotor over the total cycle is practically independent of the construction of the starting winding. This heat energy is equal to the stored energy of the rotating parts at synchronous speed, plus an amount represented by the area of a curve obtained by plotting the products of slip and load torque against time over the whole starting cycle. It was found in some actual cases that the kinetic energy of the rotating mass was equal to about 80 per cent of the total heat loss in the rotor. Thus, it is evident that a high amount of inertia inevitably causes a heating problem which cannot be ignored. Furthermore, it is impossible to reduce the amount of heat to be stored in the rotor by any change in the construction of the starting winding.

One of the ways in which this problem was considered was as follows:

The rate of heat flow into the rotor having been determined by the above means, Fourier's heat equation was integrated, considering the rotor to be a massive cylinder with heat applied to the surface. In such a case, it is theoretically possible to determine the temperature rise at the surface, at the end of any given time. This gives a result which is independent of any method of construction of the starting winding and serves to indicate the limiting condition. Such results, however, must be modified empirically, due to the actual construction being different from the assumption. It has been found possible to get a fairly good idea of the temperatures to be expected by this means, but some judgment is required in applying the results. Machines undergoing test have been put through severe starting cycles, and then opened up and examined carefully. Such examinations have shown that no damage of any kind has resulted to any of the motors as a result of tests considerably more severe than their usual starting requirements. If more than one starting cycle is to be considered, it is evident that careful consideration must be given to see that sufficient time is allowed for re-distribution of the heat generated, in order to avoid undue accumulation of heat. Special methods of ventilation would be of little value in reducing the temperature of the starting winding because the heat is generated at such a rapid rate that a flow of heat into the steel mass of the rotor must be depended on rather than convection to keep the winding cool. As a result of these studies, it has been found quite feasible to synchronize, without exceeding safe temperatures in the rotor, 3600-rev. per min. compressors requiring a starting torque of 30 per cent, and a pull-in torque of 50 per cent, and having a $W R^2$ of 2 lb-ft. squared per hp. of motor rating. While somewhat greater values of $W R^2$ per hp. may be successfully started, the heating difficulties are then more serious.

## SYNCHRONOUS CHARACTERISTICS

The synchronous characteristics of the two-pole motors are similar to those of lower speed salient pole machines. Since the amount of excitation required by any synchronous motor is a function of the number of poles, the excitation required by two-pole synchronous motors is of course very small. A 2500-hp. 0.9-power factor 3600-rev. per min. motor, for example, requires only 13.5 kw. Efficiencies of about 94.5 per cent have been obtained for 1250-hp. rating, and about 95.5 per cent for 3000 hp. rating, while slightly higher figures apply to larger sizes. Windage losses, which are included in calculating the efficiency, account for these results not equalling those of lower speed machines.

## APPLICATION

Several large two-pole synchronous motors have been built within the past five years, and these are operating successfully. However, the range of application has so far been quite limited. This is due in part to the constant speed limitation of the synchronous motor and possibly to the fact that very meager data have been published on the design, construction, and operating characteristics of motors of this type.

In sizes smaller than 800 to 1000 hp. at 3600 rev. per min., the synchronous motor is hardly competitive with the squirrel-cage or the wound rotor motor unless the need of power factor improvement justifies a higher first cost. With increasing size, however, the comparative cost of the synchronous motor improves, and this brings the synchronous motor into consideration for drives requiring greater power. Wound-rotor induction motors of several hundred hp. at 3600 rev. per min. have been built, and such motors up to 2000 or 3000 hp. have been considered. Their application, however, depends on the solution of the problem of handling large currents at the collector rings.

FIG. 6—1750-HP., 3600-REV. PER MIN. SYNCHRONOUS MOTOR DIRECT-CONNECTED TO CENTRIFUGAL COMPRESSOR

For large capacities, therefore, the choice is limited to the synchronous motor, the squirrel-cage induction motor, and the steam turbine. As the power factor of induction motors is always substantially below unity, large induction motors must be supplemented by corrective devices to make them comparable with synchronous motors.

At the present time, as nearly as we can ascertain, the largest two-pole, 60-cycle synchronous motor in operation is rated 2550 hp. This, however, does not represent the limit of sizes that can be built with the present construction. Designs have been made for a 7000-hp. 60-cycle motor and a 4000-hp., 1500-rev. per min., 25-cycle motor.

In most of the processes to which a two-pole motor could be applied, the suitability of a constant speed drive must be determined by the requirements of the individual installation. The two-pole synchronous motors now in service are used to drive centrifugal gas boosters or to drive centrifugal air compressors in connection with sewage disposal or copper refining processes.

The flotation process, for the recovery of copper from low-grade ore, requires a large volume of air at low and constant pressure and furnishes a steady load. For this service the constant speed of the synchronous motor is suitable. The high efficiency and favorable power factor of the synchronous motor may, therefore, be utilized to advantage. Copper converters also require air at approximately constant pressure and volume, except during the intervals required for emptying the converter. A number of two-pole synchronous motors are now in use for "blowing" these converters.

The "activated sludge" system of sewage disposal consists of blowing air through a porous medium into a sewage tank. The required pressure increases as the action proceeds, but the reduction in air flow offsets this pressure increase to such an extent that a constant speed motor may be applied.

Gas boosters, on the other hand, are frequently required to operate over a wide range of pressure and volume. In some cases, where the density of the gas varies, speed variation becomes a necessity in obtaining the required pressure. However, synchronous motor drive has been found satisfactory in several booster installations, compressing gas of fairly constant quality. Large compressors have been used as basic units, the variations in demand being cared for by smaller machines which may be operated at adjustable speeds. Another method involves the use of several two-pole synchronous motors, which are started and stopped in accordance with an output requirement which follows a fairly regular cycle through the day. If the explosion hazard is sufficient to warrent the use of special safeguards, the collector rings or the complete motor may be enclosed.

For high-pressure pumping the tendency has been to use higher speed to obtain the pressure that would otherwise require an excessive number of pump stages. Synchronous motors at 3600 rev. per min. have been considered for driving boiler-feed pumps in high-pressure steam plants, although the general practise calls for a motor which will allow 15 to 25 per cent speed reduction. However, two-pole constant-speed motors have been applied to this service. This would indicate that speed variation is not always essential for boiler-feed pumps. In such cases, a synchronous motor with suitable torque characteristics may be considered. For an essential drive, such as a boiler-feed pump, it is necessary to consider the reliability of the synchronous motor and its operating characteristics under unusual conditions, as well as its cost, efficiency, and power-factor. These points will be discussed later.

FIG. 7—STATOR OF TWO-POLE SYNCHRONOUS MOTOR, SHOWING METHOD OF BRACING END TURNS OF COILS

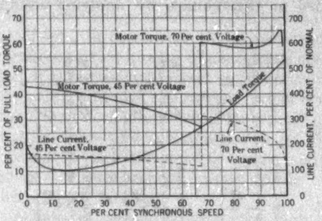

FIG. 8—TORQUE-SPEED AND LINE CURRENT-SPEED CHARACTERISTICS OF TWO-POLE SYNCHRONOUS MOTOR, WITH TWO-STEP COMPENSATOR STARTER; AND TORQUE-SPEED CHARACTERISTIC OF CENTRIFUGAL COMPRESSOR

## OPERATING CHARACTERISTICS

Since the two-pole synchronous motors are of large ratings and necessarily have low reactance, it is important to design the control equipment to start and accelerate the motor with the lowest possible inrush. Considering only the motor, full voltage starting might be used, since these motors are capable of withstanding a direct short circuit. The long end turns of the stator coils (Fig. 7) are tightly blocked to prevent movement, and severe factory tests have failed to disclose any injury to the coils after repeated short circuit at full voltage. However, the limitations of the power supply usually require reduced voltage starting, and frequently make it advisable to use two reduced voltage steps, approximately 45 per cent and 70 per cent of rated voltage, before applying full voltage to the stator.

Fig. 8 shows the torque-speed and current-speed curves of a 1500 hp., 3600-rev. per min., 60-cycle motor, based on the use of a two-step reduced voltage starter, together with a typical torque-speed curve for a centrifugal compressor with the discharge gate closed. Although the shape of the torque-speed curve of the motor may be modified to give lower break-away torque and higher torque at intermediate speeds, this change would result in a greater starting current.

The motor torque curve is therefore made to correspond roughly with the load requirements by means of starting connections as shown in Fig. 9. The neutral point of the auto transformer is closed by switch *C*. After closing the line oil-circuit breaker *F* and the compensator breaker *E*, a voltage approximately 40 per cent of normal is applied to the motor through switch *A*, which connects the motor to the taps of the auto transformer. After accelerating to about 70 per cent of synchronous speed, breaker *A* is opened, and breaker *B* is closed, increasing the voltage to approximately 70 per cent of line voltage. If the blower load is not too great, the motor may be synchronized at this voltage by applying excitation to the field. The transfer to full line voltage is made with the Korndorfer connection, by which an interruption of power is avoided. The compensator neutral is opened, and the running breaker is closed before opening the compensator breaker. During the first transfer, in which power is momentarily interrupted, the transient inrush following the transfer is considerably reduced by the reactance of the auto transformer. However, when changing to full voltage, it is desirable to maintain the circuit. A high current might otherwise flow, limited only by the transient reactance of the motor. It is of interest that, when opening the high tap *B*, before closing the line breaker *D*, there is practically no change in the voltage across the motor terminals. The upper section of the auto-transformer, serving as a series reactor, limits the voltage to the same value or even a slightly lower value than that previously obtained with the neutral point of the compensator closed.

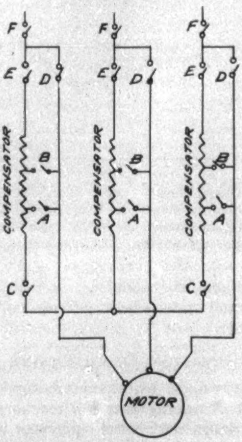

FIG. 9—STARTING CONNECTIONS FOR TWO-POLE SYNCHRONOUS MOTOR, USING TWO COMPENSATOR TAPS, WITH KORNDORFER CONNECTION FOR THE TRANSFER TO FULL VOLTAGE

If the motor is synchronized before transferring to full voltage, it becomes essential to avoid opening the circuit when making this transfer. If power were interrupted, the motor speed would drop so quickly that the motor would probably be unable to re-synchronize.

By using two taps of the compensator, and the Korndorfer connection when changing to full voltage, the current drawn from the line can usually be limited to about 300 per cent of the rated current of the motor. In most installations of large two-pole motors, the limitations of the power supply require approximately this restriction of the motor current when starting.

Where such restrictions are not necessary, and a high starting current is allowable, the use of a series reactor provides a simpler and less expensive control, by reducing the number of oil-circuit breakers and eliminating many of the interlocks and relays required for the two-step auto-transformer starter. In Fig. 10 will be found a study of starting characteristics of the 1500-hp. motor with a two-step reactor starter. These curves are based on the use of 15 per cent external reactance, which is reduced to 8 per cent when the motor reaches 70 per cent speed. The torque-speed curve is generally similar to the curve of Fig. 8, representing starting characteristics with compensator starting. The line current, however, is considerably higher. Except in locations where an exceptionally large power supply is available, this fact would probably rule out the reactor-type starter.

For some installations, the use of a permanent series reactor has been proposed. This arrangement is practical, but will involve a greater current inrush than either of the starting arrangements just described. Referring again to the 1500-hp. motor curves (Fig. 10) the permanent reactance must be less than 10 per cent to insure keeping the motor-torque curve above the load requirement. The starting current would then be approximately 500 per cent of full-load current.

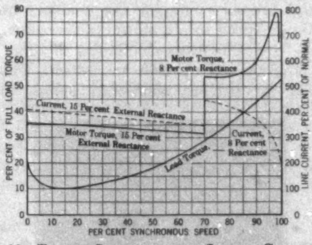

FIG. 10—TORQUE-SPEED AND LINE CURRENT-SPEED CHARACTERISTICS OF TWO-POLE SYNCHRONOUS MOTOR WITH TWO-STEP REACTOR STARTER; AND TORQUE-SPEED CHARACTERISTIC OF CENTRIFUGAL COMPRESSOR

The accelerating duty required of a 3600-rev. per min. motor is severe, and requires careful study. The rotor of a two-pole motor, whether synchronous or squirrel-cage is physically smaller than that of a lower-speed motor of equal hp. With a given amount of heat to be dissipated in the rotor, the temperature rise is necessarily greater. Ordinarily, the motors are started only once a day, or even less frequently, but provision should be made for repeated starting under emergency conditions. Where the driven machine is a centrifugal air compressor, or a gas compressor of average design having approximately 2 lb-ft.$^2$ inertia per hp. at 3600 rev. per min., motors can be designed to start twice in succession without dangerous heating of the rotor or the stator. The time interval between starts is important. Obviously a longer time interval allows more cooling as well as a better redistribution of heat between the two complete starting cycles.

Due to the unusual torque characteristics of the motor just below synchronous speed, as previously described, the synchronizing is easily accomplished in spite of the high inertia of the average centrifugal compressor. If a rotating machine is to be pulled into step from a sub-synchronous speed, its kinetic energy must be increased by an amount corresponding to the difference in speed, and this energy must be supplied in a time corresponding to less than one-half cycle at slip frequency. It is therefore important to reduce this slip to a minimum, to insure proper synchronizing and to limit the current peak which the motor may draw momentarily. Since the two-pole synchronous motor will develop approximately full load torque when running as an induction motor at 99 per cent speed, the centrifugal compressor load can be accelerated to a slip of about one-half of one per cent, and the change from induction-motor operation to synchronous operation is made with very low current inrush.

The use of a synchronous motor on any essential machine, where an outage of a few minutes may be serious, immediately raises a question regarding the operation of the motor under unusual conditions, such as momentary loss or dip of line voltage or failure of excitation voltage. With suitable torque characteristics, the synchronous motor can be arranged to continue operation after a momentary loss of a-c. power, but the control must be supplemented by additional devices to accomplish this result.

In general, if a synchronous motor falls more than a few per cent below synchronous speed, due to a momentary voltage drop, it will not re-synchronize upon return of voltage. But, if the d-c. excitation can be removed, and the oil-circuit breaker in the armature circuit remains closed, the motor can re-synchronize provided the squirrel-cage torque at sub-synchronous speeds just below synchronous is sufficient to carry the load. The characteristic curve of the 1500-hp. motor, if plotted on the basis of 100 per cent voltage, would show approximately 150 per cent torque at 98 per cent speed, and 130 per cent torque at 75 per cent speed. Thus the torque near synchronous speed is sufficient to enable the motor to accelerate, upon return of full voltage, and re-synchronize with full load on the driven machine. With automatic starting it would be advisable to allow full voltage to be applied immediately after a momentary voltage failure, rather than to go through the usual starting steps, with the resulting loss of time and reduction of speed. With a centrifugal blower load or a pump load, and an external $W R^2$ of 2 lb. ft.$^2$ per hp., the motor would drop to 94 per cent speed in one sec., after failure of voltage. If the time delay of the undervoltage device is limited to one or one and one-half sec., the motor can still be re-started without an excessive current inrush. If continuous operation is essential, it is necessary to resort to this procedure in emergency cases, although the current inrush would be higher than that normally allowed for starting. The use of a time-delay undervoltage device on the line breaker is not in itself sufficient to insure continuous operation of the synchronous motor during voltage dips, even of short duration.

The problem of removing excitation and of re-synchronizing at the proper time requires additional relay equipment and careful consideration of the effect on the supply voltage which these operations will cause.

If the field excitation is lost, the two-pole synchronous motor can operate for a very limited time as an induction motor, without overheating. Continued operation without excitation is not possible with the present designs. The use of these motors for essential service consequently requires a dependable source of direct current for excitation, or an alternative source, to which a transfer can be made quickly.

Various methods are available for removing excitation if the synchronous motor falls out of step, and for re-synchronizing after short-time interruption. However, the devices required to accomplish these steps make the control more complicated than the control required for the same type of service with induction motor drive.

The design of the two-pole synchronous motor permits the use of a large air-gap without requiring a high excitation current. An air-gap clearance of one-half inch or more is used in the larger motors. The use of forced lubrication for the bearings is an added assurance of successful operation from the mechanical standpoint.

If the motors are designed to operate at leading power factor, then, in addition to the advantage of power factor improvement, an increase in maximum synchronous torque is obtained. The pull-out torque is increased from approximately 150 per cent of full-load torque, for unity power factor operation, to 200 per cent or more for motors operating at 0.8 leading power factor. With 200 per cent available torque at rated voltage, the motor can carry full load momentarily with line voltage as low as 50 per cent of normal.

## CONCLUSION

The problems involved in the design and application of two-pole synchronous motors have been outlined so as to indicate the applications for which these motors are best adapted, and also to indicate their limitations. It is believed that there are other possible uses to which these motors have not yet been applied, and it is hoped that this paper will contribute to an understanding of the field of usefulness of the two-pole synchronous motor.

The authors wish to acknowledge their indebtedness to Mr. W. F. Dawson, under whose supervision these motors were developed, and who has contributed material for the introduction.

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## Discussion

**M. D. Ross:** The paper by Messrs. McLenegan and Summers is the first adequate paper dealing with the two-pole synchronous motor. A great deal has been written in Europe on the subject of the synchronous induction motor which uses a non-salient pole rotor, but neither the proportions nor the performance of the synchronous induction motor are comparable to the machines described. The construction of the two-pole synchronous motors is not new. As early as 1910, the company with which I am associated built a 750-hp., 2-pole, 3600-rev. per min. motor to drive a centrifugal blower. As stated by the authors, the application of these motors has been limited, which probably accounts for the lack of information to be found in technical magazines.

It has been our practise to build two-pole turbine generator rotors using solid forgings into which radial slots are machined to take the windings. The solid forging of the rotor is capable of acting as a damper winding, and the standard turbine generator can be redesigned for operation as a self-starting synchronous motor. Eddy currents are set up in the surface of the steel forging during starting, which produce ample torque for starting. The flux linking the rotor is confined to a relatively small depth on the surface of the rotor due to the well known skin effect. This effect is shown by the low voltage induced in the field winding during starting, indicating that very little flux links the field winding, but rather crosses the tops of the rotor slots. As the slip frequency decreases, the flux and eddy currents penetrate deeper into the rotor, thus giving the desirable effect of a high resistance damper winding at standstill with a high starting torque and a low resistance damper winding near synchronous speed which will allow the rotor to accelerate to a low slip.

The synchronous motor rotor differs from that of the generator only in that the steel retaining rings over the rotor coil ends are insulated from the rotor body to prohibit heating at the contact surface between them due to eddy currents. A number of synchronous motors has been built with this rotor construction, which has given entire satisfaction and has the advantage of ease of construction. Since no special damper winding is required, the amount of rotor copper is not reduced in the motor design.

The number of successive starts a motor can satisfactorily make depends largely upon the heat storage capacity of the rotor as the proportion of the heat absorbed by the cooling air during the starting cycle is relatively small. In tests of two 2700-hp., 4-pole, 1800-rev. per min. motors in which the above construction was used, it was found that the heat generated during the start had distributed itself nearly uniformly through the rotor by the time the rotor came to rest due to the good heat conductivity of the solid rotor forging which allowed the losses to escape from the surface of the rotor to the center in a relatively short time. Dangerously high temperatures cannot therefore be expected to build up on the rotor surface during several successive starts, provided the total heat storage capacity of the rotor is large enough.

One interesting feature of these motors which the authors have not mentioned is the absence of pull-in torque with no field excitation. A salient pole synchronous motor will pull into step without excitation if it is not too heavily loaded due to the difference of reluctance of the magnetic paths through the polar and inter-polar parts of the rotor. The difference in reluctance between the slotted portion of the rotor and the solid pole center is quite small and the two-pole motor will not synchronize under load unless excitation is applied.

Due to the relatively low reactance of the two-pole motor and its rapid drop in speed when disconnected from the power circuit, the design of control equipment for these motors is more difficult than for slower speed motors. When auto-transformers are used, we have so designed them that the motor is connected to the auto-transformer taps through balance coils, so that taps can be changed during starting without opening the circuit. The motors are usually started on about 40 per cent voltage, transferred to 60 per cent voltage, and are synchronized after transferring to full voltage.

The reactor method of starting described by the authors has the advantage over auto-transformers of much lower control cost and somewhat smoother operation during starting and can be used to advantage where the source of supply will allow the use of the higher starting current involved.

It is to be hoped that a better understanding of the performance of the two-pole synchronous motor by engineers interested in motor drives as brought about by papers such as the one under discussion, will open up new fields of application.

**A. B. Owen:** As the authors have indicated, the demand for 3600-rev. per min. synchronous motors comes almost exclusively from builders of centrifugal blowers and compressors. For such service this speed is as a rule too slow, as turbine-driven blowers for such applications as gas boosters are run at speeds of 10,000 to 20,000 rev. per min. However, it is the highest speed at present available in 60-cycle motors and hence the blower manufacturer must design on that basis. In centrifugal blowers and compressors, the pressure is developed by using high tip velocities to impart high velocities to the gas and then converting this velocity into its equivalent pressure. The blower designer is always interested in the highest possible tip velocity without resorting to disproportionately larger diameters.

In the development of the first successful synchronous motors for driving blowers, about the year 1914, the problem of a sufficient starting torque was naturally prominent; in fact, it might fairly be said that this problem was and is today the only problem of a motor design to distinguish it from the design of a corresponding turbine generator. Fortunately, the starting requirements of a motor driven blower are simple and easy. Only sufficient torque is required to break the rotors away from rest and to accelerate them. The work done in moving the air at slow speed is negligible; consequently, at the start when the rotor frequency is a maximum, the required torque is a minimum and it is only as the rotor frequency drops due to increase of speed that the required torque increases—an ideal starting condition.

Even with this favorable condition the problem of the starting winding is difficult, and not the least of the difficulties is to handle the expansion in the axial conductors. High heat must be expected under starting conditions and only a part of this heat can be conducted away even in such an excellent arrangement as that shown by the authors of this paper. The older practise on Elliott motors of this type was to attach the conductors to end rings having quite a measure of axial flexibility. Expansion from heat can fairly be called an irresistible force and if provision is not made for necessary movement, joints will be broken.

A recent development that may be of interest consists in using the steel of the solid-forging type of rotor as the starting winding. Each tooth of the rotor is an axial conductor, connected at its ends to the solid body of the shaft. Its resistance is high and its heat storage capacity and also its heat conduction to the shaft are excellent.

This simple construction, entirely free from joints and special materials, makes it ideal for the particular application under consideration, and it has been used successfully for the last four or five years in motors from 750 to 2200 hp. There seems to be no reason why it should not be equally applicable to motors of larger sizes. These motors will break away and accelerate to about 30 per cent speed on the application of a starting voltage as low as 35 per cent of rated voltage, though 40 to 45 per cent is desirable on the first starting point.

I wish to endorse the method of starting such motors by increasing the applied voltage without opening the stator circuit. This is very desirable in order to avoid shock to the rotor and possible distortion of the end connection of the stator winding.

**R. B. Williamson:** The authors say: "compressors requiring a starting torque of 30 per cent, and a pull-in torque of 50 per cent, and having a $W R^2$ of 2 lb-ft.$^2$ per hp. of motor rating." I want to ask if that is the combined compressor unit or just the compressor alone.

**I. H. Summers:** With reference to Mr. Ross' discussion, particularly in regard to building a synchronous motor with a solid-core rotor, I may say that we have also built a machine of this construction and tested it. We feel that a laminated construction with a properly designed squirrel-cage winding is probably a more flexible design because, by changing the material, or the dimensions of the windings and the retaining wedges above these windings, different characteristics can be obtained for different purposes.

With regard to his point that a round-rotor synchronous motor does not have pull-in torque, I wish to point out that in the motor we tested and for which curves are given in the paper, the torque is very large at speeds close to synchronism, so that the motor reaches a slip of probably 0.5 per cent at the time the field is applied, which makes it very easy to synchronize.

Mr. Ross evidently felt that the temperature rise during a cycle in which several starts are made is not a serious problem, provided the motor be made large enough, and we agree thoroughly with that. Of course the point is that the motor must be made large enough. In this connection I have prepared some curves showing the temperature distribution to be expected in a cylindrical rotor, assuming a homogeneous mass of iron with heat applied to the surface. These curves indicate in a general way what maximum temperatures would be obtained under this assumption.

Mr. Owen, in his discussion, pointed out that the problem of starting a centrifugal compressor is not serious. The main thing is to have sufficient torque to accelerate its inertia without overheating the motor and we agree thoroughly with this also. In these applications the inertia of the load is often very large and is what limits the size of the motor if repeated starts have to be made. With a two-pole motor, having a rotor of as small size as it normally would be in this design, the problem is more serious than it appears at first sight.

With regard to his point about the expansion of the conductors being a serious problem, I might mention that although the photograph in our paper does not show it, the squirrel-cage winding which we use is formed of copper ribbons and is so constructed that a wave is placed in the ribbons at the ends of the rotor to take up the expansion and this completely prevents all trouble which might otherwise result from restraint of the expansion.

In answer to Mr. Williamson's question as to whether the figure given in the paper of 2 lb-ft.$^2$ per hp. rating applies only to the compressor or to the combined unit, I may say that that was intended to apply to the compressor only.

Consider a homogeneous cylinder with heat applied uniformly all over the cylindrical surface. Assume that this heat is known as a flow function of time in terms of power per unit area. The problem of determining the temperature distribution at any point in the cylinder at any time may be reduced to the solution of a partial differential equation.

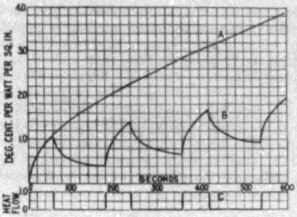

FIG. 1

The heat equations are

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \theta}{\partial r}\right) = \frac{p}{\alpha^2}\theta \qquad (1)$$

$$f = -c\frac{\partial \theta}{\partial r} \qquad (2)$$

where
$r$ is the radius of the cylinder
$p$ is time differentiating operator
$f$ is heat flow
$c$ is conductivity
$\theta$ is temperature
$\alpha^2$ is the diffusivity

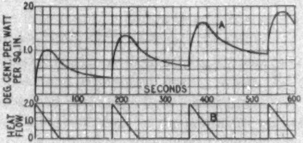

FIG. 2

Substituting the boundary conditions that the cylinder is not hollow and that $f = f_0$ at $r = r_0$ and solving, the temperature is found in operational terms

$$\theta = \frac{1}{n\,c}\,\frac{J_0(n\,r)}{J_1(n\,r_0)}\,f_0 \qquad (3)$$

where $n = j\dfrac{\sqrt{p}}{\alpha}$

$j = \sqrt{-1}$

$J_0, J_1$ = Bessel functions

In order to get this solution in explicit form it is convenient to expand it in terms of partial fractions.[1] Owing to lack of space this development will be omitted and the result simply stated.

$$\theta = -\frac{2\,\alpha^2}{c\,r_0}\left[\frac{1}{p} + \sum \frac{J_0\,(y\,a_n)}{J_0\,(a_n)}\;\frac{1}{p + \left(\frac{a_n\,\alpha}{r_0}\right)^2}\right] f_0$$

where the summation is taken over all the positive roots of $J_1\ (x) = 0$, $a_n$ representing these roots. In this expression $y = r/r_0$.

Now the flow function is taken as a constant flow directed inward, in the Heaviside notation.

$$f_0 = -F\,1 \tag{5}$$

When this is substituted and the operations performed according to the Heaviside rule, the final solution after simplification is:

$$\frac{\theta}{F} = \frac{2\,r_0}{c}\left[\left(\frac{\alpha}{r_0}\right)^2 t + \left(\frac{y^2}{4} - \frac{1}{8}\right) - \sum \frac{J_0\,(y\,a_n)}{a_n^2\,J_0\,(a_n)}\,\epsilon^{-\left(\frac{a_n\,\alpha}{r_0}\right)^2 t}\right] \tag{6}$$

where $t$ is time.

At the surface of the cylinder where the temperatures are maximum this reduces to:

$$\frac{\theta}{F} = \frac{2\,r_0}{c}\left[\left(\frac{\alpha}{r_0}\right)^2 t + \frac{1}{8} - \sum \frac{1}{a_n^2}\,\epsilon^{-\left(\frac{a_n\,\alpha}{r_0}\right)^2 t}\right] \tag{7}$$

This curve is plotted in Fig. 1A herewith for an iron cylinder of 10 in. radius in which $\alpha^2 = 0.0188$ sq. in. per sec. and $c = 1.14$ watts per sq. in. per deg. cent. per in. Fig. 1B is the temperature when the flow function is intermittent as in Fig. 1C. Fig. 2A is the temperature when the flow function is as shown in Fig. 2B and the total heat applied is the same as in Fig. 1C. It will be noted that the maximum temperatures are practically the same in either case so that it is only necessary to know the total heat applied to get an approximate idea of the answer. The ordinates in either figure are to be multiplied by average watts per square inch for one heat cycle to get degrees centigrade.[2]

In the application of these curves to a practical problem in the starting of synchronous motors it should be remembered that herein no heat is assumed to escape from the surface. This would probably not modify the result radically, however, and to offset it there is the consideration that the rotor construction is not perfectly homogeneous, having slots and other irregularities. At best the curves are a rough approximation to a practical case but it is felt that they do serve to illustrate some interesting points in connection therewith.

**D. W. McLenegan:** Mr. Ross mentioned the smoother starting which is possible with the reactor method. If the motor could be designed so that its impedance increased rapidly at intermediate speeds, this type of starting would be ideal. However, as the motor accelerates, the impedance does not rise sufficiently to increase the voltage drop across the motor and provide a motor torque corresponding to the increasing load torque. It is therefore impossible to use a constant external reactance throughout the accelerating period except by making this reactance very small and accepting a high initial current. The reactor is cut out in steps, and this procedure involves abrupt changes in the motor current.

Mr. Owen mentioned the desirability of maintaining the circuit while increasing the applied voltage during the starting period. However, with the auto-transformer method described in the paper, the magnetizing current of the auto-transformer is not interrupted when changing taps, and consequently the inrush is materially reduced due to the reactance of the auto-transformer. It has been our experience that the coil bracing is adequate to prevent any distortion of the end turns of the stator winding.

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[1] The writer is indebted to Mr. R. H. Park for showing him how to make this expansion and simplify the result.

[2] The author is indebted to Mr. S. Paglinca for assistance in the numerical work and plotting the curves in the figures.

# Heat Losses in D-C. Armature Conductors

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E. WAYNE,[2]

and

M. L. HENDERSON[3]
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***Synopsis.**—The pioneer paper on this subject of copper losses in armature conductors was presented by A. B. Field.[4] Since then Field's fundamental premises have been adopted by practically all who have contributed to this subject, both in this country and abroad, although the method of presentation has been modified as the individual thought best. Thus one of the present authors has favored a vector method of analysis that seems to him to have marked advantages. In this paper the vector method is extended to the case of the d-c. machine.*

*Without doubt, it is generally believed that there are extra losses in the armature coil of a d-c. machine when it is undergoing commutation, but that during the major portion of the time, since the current is steady, the loss in the coil is correctly computed by squaring the value of the current and multiplying by the true or ohmic resistance of the coil. This view, however, is not correct. The disturbance in the coil current produced by the process of commutation persists throughout the cycle so that at no time is the current uniformly distributed over the cross-section of the conductor. Although the disturbance and resulting extra loss factor are greatest during commutation, the extra losses are present at all times, even while the current in the coil is steady. The procedure for finding the extra losses is simple. First, the time variation of the coil current must be known and analyzed for its harmonic components. In the present analysis it is assumed to be trapezoidal because this is, at once, a simple and a desirable manner of variation. The extra loss is then computed for each harmonic component as described in "Heat Losses in the Conductors of A-c. Machines," by W. V. Lyon, and "Reduction of Armature Copper Losses," by I. H. Summers. The total extra loss is the sum of the component extra losses. In case there are several coils side by side, as is usual in a d-c. armature winding, the average extra loss in the coils for any harmonic component of current is computed as if the coils that are side by side were connected in parallel and carried the vector sum of the currents in these coils; assuming that the coils are alike and are symmetrically arranged. If there are more than two coils side by side, the losses in them are not the same.*

*It is important to realize that the armature copper loss in a d-c. generator is not correctly computed by squaring the armature current and multiplying by the measured armature resistance between brushes; and furthermore, that it is more important to laminate and properly arrange the armature conductors of a large d-c. generator than it is to do so in the case of an a-c. generator.*

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## PART I

ALTHOUGH there have been excellent papers[5] on this problem of the armature copper loss in a d-c. machine, as far as the authors are aware it has received no serious consideration in this country and it is not generally realized that the time-honored method of computing the armature copper loss does not give a correct value of the loss. The error may range from 10 or 20 per cent in a small machine to several hundred per cent in a large and poorly-designed one. The determination of this loss and the factors which influence it are thus matters of prime importance. Due to the process of commutation the current in the armature coil of a d-c. machine is an alternating one which has a fundamental and various harmonic components. The problem of an armature coil that carries a sinusoidal current has been investigated by several writers since Field[4] first published his solution of the problem. The experimental results[6] which have since been obtained agree so closely with the computations that we are warranted in extending the application of the theory to this problem of the heat losses in the conductors of a d-c. armature when not only the fundamental but all of the harmonic components are present in the current. Due to the fact that the losses, produced by the higher harmonics in the current, increase about as the square root of the frequency, the extra loss factor for a d-c. armature is greater than the extra loss factor for an a-c. armature under the same conditions of speed, poles, size, and arrangement of the armature conductors. Laminated conductors are indispensable in the design of a-c. generators, but it is even more important to laminate and properly arrange the armature conductors of a d-c. machine.

One phase of the present investigation was to compare the observed and computed results when the current in an embedded coil (Fig. 1) is commutated so that it varies as the current does in the armature coil of a d-c. generator. A typical curve showing the time variation of the current is shown in Fig. 2. The coil shown in Fig. 1 consisted of 51 turns of copper ribbon one inch wide by 0.0062 inch thick. Five No. 40 wires were attached to but insulated from the ribbon at uniformly spaced intervals. One of these wires was 1/16 inch from the upper edge of the ribbon; one, 1/4 inch from the upper edge; one at the middle; one, 1/4 inch from the lower edge and one, 1/16 inch from the lower edge. The ribbon and the attached wires were then wound to form the coil, a cross-section of which is shown in Fig. 3. These exploring wires enable one to make a direct measurement of the current density at five different points in the ribbon. Inasmuch as an exploring wire and a filament of the ribbon in the same horizontal plane link the *same flux* the difference in their potentials is the resistance drop in this filament of the ribbon and is, therefore, proportional to the current density in this filament. The arrangement of the coil, commutator, and oscillograph vibrators is shown in Fig. 4. The current-density vibrator was calibrated by sending a known value of steady current through the coil. Five calibrations were made, one for each exploring wire. The commutator was driven so that the current in the coil was reversed 120 times a sec., giving a 60-cycle variation. The oscillograms obtained are shown in Fig. 5 (a. b. c. d and e). These oscillograms show the current in the coil and the current density at each of the five points. The scale of the current is such that the curve also shows the average current density and may thus be compared with the actual current density. The computed time variation of current density at each point is also shown. The close agreement between the observed and computed values shows that, under the conditions existing during this measurement, the premises on which the theory is built—*viz.*, those adopted by Field—are amply justified.

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[3] Graduate Student in Electrical Engineering 1926-27, Massachusetts Institute of Technology.

[4] *Eddy Currents in Large Slot-Wound Conductors*, A. B. Field, A. I. E. E., 1905, p. 761.

[5] L. Dreyfus, "Zusätzliche Kommutierungsverluste bei Gleichstrommaschinen," *Elekt. und Masch.* XXXII, 281, 1914.

L. Dreyfus. "Die Theorie der zusätzlichen Kommutierungsverluste von Gleichstrommaschinen," *Arch. fur Elek.* III, 273, 1915.

L. Dreyfus. "Zusätzliche Kupferverluste durch Stromverdrangung bei Einankerumformern," *Arch. fur Elek.* IV, 42, 1915.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Feb. 13-17, 1928*

[6] TRANS. A. I. E. E., 1922 Vol. 41, p. 213, and present paper.

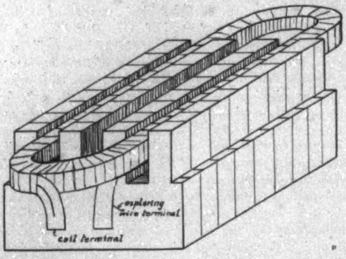

FIG. 1—GENERAL ARRANGEMENT OF COIL AND EXPLORING WIRE

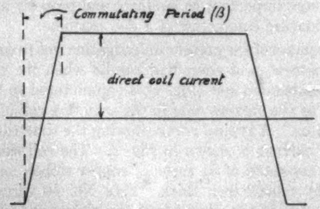

FIG. 2—CURVE SHOWING TIME VARIATION OF COIL CURRENT

The computed values of the current density were obtained in the following manner. The time variation of the current in the coil was first analyzed for its harmonic components. By means of the fundamental relation[7] between the current in the conductor and the current density at any point, the time variation of the current density at each point for each harmonic component of the current up to and including the eleventh harmonic, was determined. By combining the harmonic variations in current density at one point the resultant variation in the current density at the point was determined and plotted. The oscillograms show distinctly that the current density is greater in the upper portion of the conductor, as it is when the current is sinusoidal; that the higher harmonics are practically confined to the upper portion of the conductor; that during the commutating period the current is flowing in opposite directions in the conductor at the same time; that at the beginning of each half-cycle the current is most unevenly distributed, but toward the end of the half-cycle the distribution has become nearly uniform. In describing the phenomenon, it might be said that the continued reversal of the current, due to the process of commutation, produces a turbulence in the current flow of such a nature that the current distribution consists of a series of harmonic components, each one of which can be determined in the same manner in which the distribution is determined when the current variation is purely sinusoidal. This turbulence is not confined to the commutation period alone but continues throughout the cycle. The

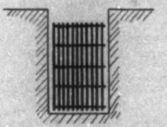

FIG. 3—CROSS-SECTION OF COIL AND EXPLORING WIRES

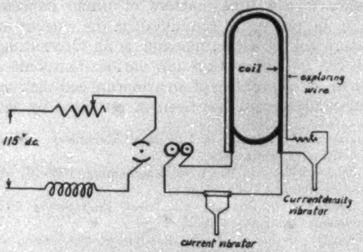

FIG. 4—ARRANGEMENT OF COMMUTATOR, COIL, AND OSCILLOGRAPH VIBRATORS

heat loss in the conductor is the sum of the losses due to the individual harmonic components of current. Each of these component losses can be determined by the same procedure that is used in computing the loss in an a-c. generator. Computation of the resistance ratio for a d-c. machine is thus a much more laborious process, than is the computation of the ratio for an a-c. generator. The resistance ratio may be defined in one of two ways, either as the ratio of the actual loss to the loss that would occur if the same coil current were uniformly distributed in the conductor, or as the ratio of the actual loss to that as computed according to the standardization rules of the A. I. E. E. These ratios would be somewhat different. In our case the measured loss in the coil was 14.8 watts and the calculated loss, 14.4 watts. In the calculation, only the harmonics up to and including the 13th were considered. The loss due to the fundamental, or 60-cycle, component is 12.9 watts, showing that the loss due to the harmonics is 10.4 per cent of the total. When this measurement of power loss was made a different commutator was used, and the wave form of the coil current is shown in Fig. 5 (f). The maximum flux density in the teeth during these power measurements was approximately 1000 gausses.

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[7] W. V. Lyon, *Heat Losses in the Conductors of A-C. Machines*, TRANS. A. I. E. E., 1921 Vol. 40, p. 1361.

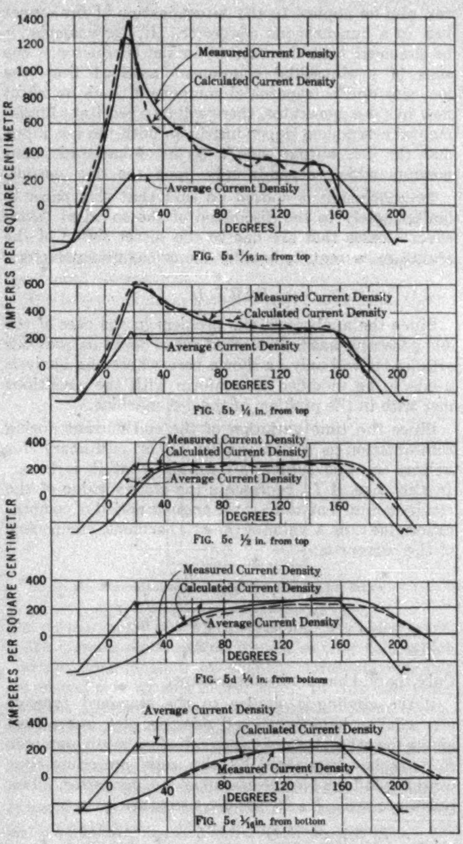

FIG. 5a 1/16 in. from top

FIG. 5b 1/4 in. from top

FIG. 5c 1/2 in. from top

FIG. 5d 1/4 in. from bottom

FIG. 5e 1/16 in. from bottom

FIG. 5—a, b, c, d, e, OSCILLOGRAMS AND CALCULATED CURVES OF CURRENT DENSITY AT DIFFERENT POINTS

There is another point of interest. It is the heat loss in the coil during the period of commutation. If it be assumed that the variation of the total current, and of the current density during the time of commutation is linear, an approximate value of the ratio of the actual heat developed, to that which would be developed if the current density were uniform, can be calculated. In our case this ratio is approximately 5, that is, during commutation, the conductor acts like one having a resistance approximately 5 times as great as it actually is.

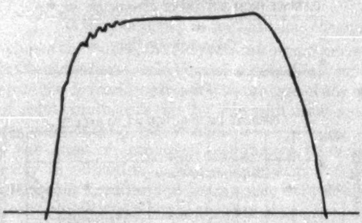

FIG. 5f—WAVE FORM OF COIL CURRENT WHEN LOSS MEASUREMENTS WERE MADE

With 60-cycle sinusoidal current in the conductor the measured and computed resistance ratios are 1.66 and 1.61 respectively. Figs. 6 and 7 show the observed and computed current densities and their phase-angles with respect to the total current in the conductor.

All of these results seem to show that the original premises as stated by Field are so nearly true, even when applied to this problem of the commutated current, that the errors in the computation are scarcely of engineering importance.

When these principles are applied to the determination of the armature copper loss in a d-c. machine it must not be expected that the accuracy of the result will equal that attained in the case of the a-c. generator. There are two principle reasons for this. First it is improbable that the variation of the current during the commutation period will be known with sufficient precision. Poor commutation may give rise to harmonics that will materially increase the copper loss. Secondly, in d-c. machines, coils which undergo commutation at slightly different times are placed side by side in the slot; producing a phase displacement between the components of the currents in these adjacent coil sides which is directly proportional to the order of the harmonic. Some of the higher harmonics will thus be approximately in opposition. This condition violates one of the Field premises, *viz.*, that the current density should be the same in any horizontal plane. Three approximate methods for computing the loss in this case are described in the Part II of the paper.

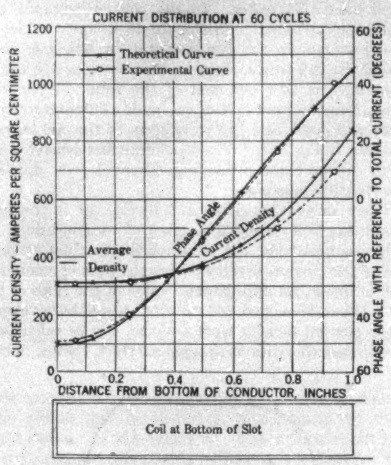

FIG. 6

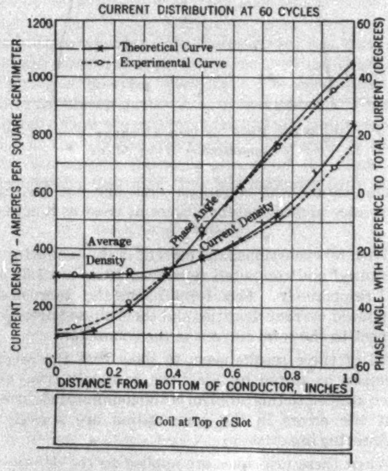

FIG. 7

FIGS. 6 AND 7—COMPARISON OF MEASURED AND COMPUTED CURRENT DENSITIES

The general principles that have been discussed here can also be applied to the determination of the copper loss in a synchronous converter. If, for example, it be assumed that the current in the conductor is the sum of a sinusoidal component received from the a-c. side and a trapezoidal component, such as might flow in a d-c. generator, there will be a resultant fundamental component depending upon both the a-c. input and the d-c. output, and a series of harmonic components which depends only upon the d-c. output.

In conclusion it should be said that this paper is limited solely to the discussion of the so-called "skin-effect" losses that are due to the direct action of the armature current in heating the armature conductors.

## PART II

Since the analysis of the problem in the case of the a-c. generator has been worked out in detail in previous articles,[8] it will only be shown here where the analysis needs to be modified to conform with the conditions met with in the problem of the d-c. machine.

Since the time variation of the coil current during commutation is seldom known, it is customary for writers on this subject to assume that it is linear. In this case, if $I_{dc}$ represents the steady value of the conductor current and $\beta$ is the angular period of commutation, the r. m. s. value of the $n$th harmonic component of the current is:

$$I_n = \frac{4}{\pi\sqrt{2}} \, \frac{\sin\dfrac{n\beta}{2}}{\dfrac{n\beta}{2}} \, \frac{1}{n} \, I_{dc}$$

Only the odd harmonics are present.

If the winding is similar to the standard type of a-c. winding having two coil sides per slot, one placed above the other, the resistance ratio for the $n$th harmonic $K_n$, can be determined by the same procedure that would be followed in the case of an a-c. generator. The resistance ratio, $K_0$, for the d-c. armature is then

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[8] A. E. Gilman, *Eddy-current Losses in Armature Conductors*, TRANS. A. I. E. E., Vol. 39, 1920, Part I, p. 997.

W. V. Lyon, *Heat Losses in the Conductors of A-C. Machines*, TRANS. A. I. E. E., Vol. 40, 1921, p. 1361.

W. V. Lyon, *Heat Losses in Stranded Armature Conductors*, TRANS. A. I. E. E., Vol. 41, 1922, p. 37.

I. H. Summers, *Reduction of Armature Copper Losses*, TRANS. A. I. E. E., Vol. XLVI, 1927, p. 101.

For a brief bibliography see TRANSACTIONS of A. I. E. E., Vol. 41, page 213. A paper by F. W. Carter has just come to out attention. "Parasitic Currents Losses in Bar-wound Direct-current Armatures." *Jl.* I. E. E., Vol. 65, p. 1002.

$$K_0 = \frac{\displaystyle\sum_{n=1}^{n=n}\left(\frac{\sin\frac{n\beta}{2}}{\frac{n\beta}{2}}\,\frac{1}{n}\right)^2 K_n}{\displaystyle\sum_{n=1}^{n=n}\left(\frac{\sin\frac{n\beta}{2}}{\frac{n\beta}{2}}\,\frac{1}{n}\right)^2} \quad \text{(First definition)}$$

$$\text{or } K_0' = \frac{\left(\frac{4}{\pi\sqrt{2}}\right)^2 \displaystyle\sum_{n=1}^{n=n}\left(\frac{\sin\frac{n\beta}{2}}{\frac{n\beta}{2}}\,\frac{1}{n}\right)^2 K_n}{1-\frac{\beta}{\pi}} \quad \text{(Second definition)}$$

The upper limit of $n$ should be as large a value as is considered necessary.

The latter definition assumes that the brushes short-circuit $\frac{\beta}{\pi}$ of the armature coils per pole when the d-c. measurement of armature resistance is being made.

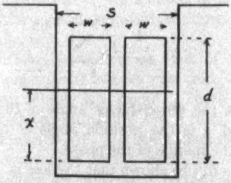

Fig. 8—Cross-Section of Coil and Slot

D-c. armatures are often wound so that coils which undergo commutation at slightly different moments are placed side by side in the slot. In this case three different approximations are suggested. There are no data which show their relative accuracy.

1. The difference in time of commutation can be ignored, and the resistance ratio computed as described above. This approximation is the simplest of the three. It neglects the phase relation of currents that are side by side in the slot, which in the case of some of the higher harmonics is approximately 180 deg. This method can be applied to any type of symmetrical winding whether of solid or of laminated conductors. The computed value of the loss would probably be too great.

2. It may be assumed that the current density in any conductor is uniform in any horizontal plane but is not necessarily the same in the different conductors that lie side by side in the slot, (Fig. 8). The current densities in the conductors are respectively $c_1$ and $c_2$ in the plane through $X$. A simple case of but two conductors has been chosen as an illustration.

The following differential equations for the current densities must be satisfied:

$$\frac{d^2\,c_1}{d\,x^2} = j\,\frac{4\,\pi\,\omega}{\rho\,s}\left(c_1\frac{w}{2} + c_2\frac{w}{2}\right)$$

$$\text{and}\quad \frac{d^2\,c_2}{d\,x^2} = j\,\frac{4\,\pi\,\omega}{\rho\,s}\left(c_1\frac{w}{2} + c_2\frac{w}{2}\right)$$

When the currents are equal in magnitude but differ in phase by a time angle $\theta$, it follows that the copper loss in each conductor is

$$R\left[\left(I\sin\frac{\theta}{2}\right)^2 + \left(I\cos\frac{\theta}{2}\right)^2 M_r\right]$$

where: $R$ is the true resistance of one conductor
$I$ is the current in each conductor
$M_r$ is the real part of $\alpha\,d\coth\alpha\,d$

$$\alpha\,d = 2\,\pi\,d\sqrt{\frac{j\,2\,f\,w}{\rho\,s}}$$

$f$ is the frequency of the harmonic considered.

This shows that when the currents are in opposition the loss is the same as it would be with steady direct current. This method is readily extended to the case of any number of solid conductors side by side with other conductors carrying current below them.

In the case of laminated conductors there is no difficulty in obtaining a simple solution provided the armature coils are alike and are symmetrically arranged. The loss in such a winding is the sum of two component losses. The first is the loss that would be produced if there were in each coil a steady direct current equal in magnitude to the r. m. s. value of the commutated coil current. The second of these component losses is the sum of the extra[9] losses due to a series of harmonic components of current. Any one of these harmonic components of current is the vector sum of the actual harmonic components of the currents in any row[10] of conductors in the same slot. The extra loss due to any one of these harmonic components is then computed as if the coils that are side by side in the same slot were in parallel. This can be done by following the same procedure that would be followed in the case of an a-c. generator. Reduced to a formula the loss becomes

$$R\,I_{dc}^2\left[\left(1-\frac{2}{3}\,\frac{\beta}{\pi}\right) + \frac{8}{\pi^2}\sum_{n=1}^{n=n}\left(\frac{\sin\frac{n\beta}{2}}{\frac{n\beta}{2}}\,\frac{1}{n}\,\frac{\sin\frac{n\,q\,\Delta}{2}}{q\sin\frac{n\,\Delta}{2}}\right)^2(K_n-1)\right]$$

Where: $R$ is the true or ohmic resistance of the armature coils all connected in series;

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[9] In excess of the loss as computed with direct current.

[10] In a circumferential direction and *not* in a radial direction.

$I_{dc}$ is the maximum value of the coil current;

$\rho$ is the angular duration of commutation;

$\Delta$ is the time angle—on fundamental scale ($n = 1$)—between the moment at which one coil of a row in any slot is commutated and at which the next coil of the row is commutated;

$q$ is the number of coils in a row;

$K_n$ is the resistance ratio of the winding for the $n$th harmonic, computed as it would be for an a-c. generator which had the coils in any row connected in parallel.

The summation is taken for all odd values of $n$.

The form of the time variation of the coil current is assumed to be trapezoidal.

3. It may be conceived that the currents, $I_1$ and $I_2$, (Fig. 9) consist of the following components.

$$I_1 = \frac{1}{2}(I_1 + I_2) + \frac{1}{2}(I_1 - I_2)$$

$$I_2 = \frac{1}{2}(I_1 + I_2) - \frac{1}{2}(I_1 - I_2)$$

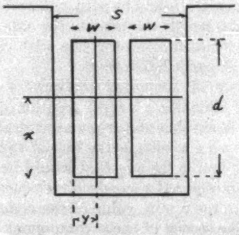

Fig. 9—Cross-Section of Coil and Slot

Let it now be assumed that these components are distributed over the cross-section of the conductors as if they existed separately. The first components, being equal, are distributed according to Field's theory. Let the current density in the plain through $x$ be $c_x$. The second components are in time opposition in the conductors and it may reasonably be assumed that they are distributed as they would be in an infinite sheet lying close to a region of infinite permeability. The vector current density in the plane through $y$ is then of the form $c_y = A \cosh \alpha_2 y$; where $\alpha_2 = 2\pi\sqrt{j\frac{2f}{\rho}}$.

The total vector current density at the point $(x, y)$ is then $(c_x + c_y)$ and the loss in one conductor is

$$\int_0^{\frac{w}{2}} \int_0^{d} \rho\,(c_x + c_y) \,.\, (c_x + c_y)_{\text{conjugate}}\, d\,x\,d\,y$$

In the case of equal currents differing by a time-phase angle of $\theta$ this expression readily reduces to

$$R\left[\left(I\cos\frac{\theta}{2}\right)^2 M_{r1} + \left(I\sin\frac{\theta}{2}\right)^2 M_{r2}\right]$$

Where $M_{r1}$ is the real part of $\alpha_1 d \coth \alpha_1 d$, and $M_{r2}$ is the real part of $\alpha_2 \frac{w}{2} \coth \alpha_2 \frac{w}{2}$;

$$\alpha_1 d = 2\pi d\sqrt{j\frac{2f\,2w}{\rho s}} \quad \alpha_2 w = 2\pi w\sqrt{j\frac{2f}{\rho}}$$

$R$ is the true resistance of one conductor and $f$ is the frequency of the particular harmonic considered. This method can be used with any symmetrical type of winding that has not more than two conductors side by side in the slot.

The armature copper loss in a synchronous converter can readily be computed if it be assumed that the current in a coil consists of two components, one of which is the trapezoidal current that would flow if the machine were operated as a d-c. generator, and the other is the sinusoidal current that would flow if the machine were operated as a synchronous motor. This assumption may not be true during the commutation period. The current in an armature coil is

$$i = \sqrt{2}\, I_{ac} \sin(\omega t - \theta - y)$$

$$- \frac{4}{\pi} I_{dc} \sum_{n=1}^{n=\infty} \frac{\sin\frac{n\beta}{2}}{\frac{n\beta}{2}} \frac{1}{n} \sin n\,\omega t$$

Where $\theta$ is the power-factor angle of the alternating current and $y$ is the position angle of the coil with respect to the middle of the phase.

It can readily be shown that the loss is

$$R\left[I_{ac}^2 K_1 + \frac{8 I_{dc}^2}{\pi^2} \sum_{n=1}^{n=n} \left(\frac{\sin\frac{n\beta}{2}}{\frac{n\beta}{2}} \frac{1}{n}\right)^2 K_n\right.$$

$$\left. - \frac{4\sqrt{2}}{\pi} I_{dc} I_{ac} \frac{\sin\frac{\beta}{2}}{\frac{\beta}{2}} k_b K_1 \cos\theta\right]^{11}$$

Where: $R$ is the series resistance of all of the armature coils;

$K_1$ is the resistance ratio of the winding for the fundamental;

$K_n$ is the resistance ratio of the winding for the $n$th harmonic;

$k_b$ is the breadth factor for the winding;

$\beta$ is the angular time of commutation.

The higher harmonics in the conductor current produce such a rapid variation in the tooth flux density that it is no longer uniform, being greater at the surface

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[11] This assumes that the armature coils are *not* arranged side by side in the slots.

than at the center of the laminations. There thus appears to be a possibility that the resulting density at the surface of the lamination, due to the leakage flux and that which enters the teeth from the air-gap, may be so great as to reduce the permeability to such a small value that one of the fundamental premises of the Field theory—*viz.*, that the permeability is very great—is seriously violated. This phenomenon of skin effect in iron laminations is readily solved if the permeability is assumed to be constant. Actually, the permeability goes through a cyclic series of values. Since, however, the skin effect is exaggerated by choosing a relatively high permeability, say 4000, we shall do so, although the average value may be much less. For a similar reason we will use a relatively low resistivity, 36 microhms per centimeter cube. The angular depth to be used in computing the skin effect in 14 mil iron at 900 cycles (15th harmonic for 60-cycle fundamental) is:

$$\alpha\, d = 2\,\pi \times \frac{0.014 \times 2.54}{2} \sqrt{\frac{2 \times 900 \times 4000}{36 \times 10^{-6} \times 10^{9}}}$$

For this value of $\alpha\, d$ the ratio of the density at the surface to the average density is but 1.4 and skin effect is thus playing no important part in the problem.

As an illustration of the method of calculating the loss factor for a given armature winding, the following example is taken.

The armature considered is that of a 6-pole, d-c. machine operating at 900 rev. per min. The winding is full pitch, simple lap wound. There are two coils per slot, each consisting of a single turn, and the total number of coils is 216. In the armature slot the conductors are arranged two in width and two in depth. The conductors are solid, and rectangular in section. Principal conductor and slot dimensions are as follows:

Conductor width, $\frac{w}{2}$ = 0.405 cm.

Total width of copper in slot, $w$ = 0.81 cm.
Conductor depth, $d$ = 1.40 cm.
Slot width, $s$ = 1.19 cm.

The fraction of a cycle during which a coil is short-circuited is $\frac{\beta}{\pi} = 0.0725$. On the assumption that the current—time curve for the coil is trapezoidal, the r. m. s. value of the $n$th harmonic component of coil current is:

$$I_n = \frac{4}{\pi\sqrt{2}}\; \frac{\sin \frac{n\,\beta}{2}}{\frac{n\,\beta}{2}}\; \frac{1}{n}\, I_{dc}$$

$$\text{or} \quad = \frac{4}{\pi\sqrt{2}}\; \frac{\sin \frac{n\,\beta}{2}}{\frac{n\,\beta}{2}}\; \frac{1}{n}\; \frac{I_e}{\sqrt{1 - \frac{2}{3}\,\frac{\beta}{\pi}}}$$

where $I_{dc}$ is the magnitude of the direct current in the coil and $I_e$ is the r. m. s. value of this current. Table I shows the mean-square values of the harmonics up to the fifteenth. The mean-square value of the coil current is 95.17 per cent of the square of its maximum, or d-c. value.

When there is a row of conductors side by side in the slot, carrying currents equal in magnitude but different in phase, the loss due to any harmonic current is taken as the sum of the normal ohmic loss due to the currents actually flowing and the extra loss calculated as if each of the conductors in the row carried the *vector average* current for the row. This is the second approximate method. The $n$th harmonic extra loss factor for the embedded portion of the conductor is

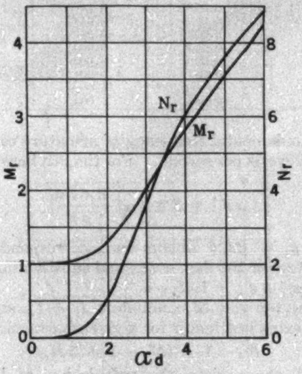

FIG. 10—VALUES OF $M_r$ AND $N_r$

$$K_n - 1 = (M_r - 1) + \left[ \left( \frac{I_b}{I_{av}} \right)^2 + \left( \frac{I_b}{I_{av}} \right) \cos\delta \right] N_r.$$

$I_{av}$ is the magnitude of the vector average of the currents in conductors of the row and $I_b$ is the magnitude of the vector current flowing in the slot below the row in question per conductor in that row. $\delta$ is the angular phase difference between $I_{av}$ and $I_b$. $M_r$ and $N_r$ are taken at the value of $\alpha\, d$ for the harmonic considered.

In the example considered, successive armature coils are commutated at intervals of 1/216 revolution. The $n$th harmonic components of current in conductors side by side are out of phase by an angle $\theta = 5\,n$ degrees. With two conductors in a row across the slot the ratio of the vector average current to each current, is

$$\frac{I_{av}}{I} = \cos \frac{1}{2}\, n\, \theta = \cos n \times 2.5 \text{ deg.}$$

Table I shows the value of the square of this ratio for harmonics up to the fifteenth.

The winding scheme used in this armature causes the currents in conductors in the same radial plane to be commutated simultaneously so that the phase displacement between the harmonics in the top and bottom rows is zero, *i. e.*, $\delta$ is zero.

TABLE I.
HARMONIC ANALYSIS OF COIL CURRENT

| Order of Harmonic | Mean-square values | | Vector average factor |
|---|---|---|---|
| $n$ | $\left(\frac{I_n}{I_{dc}}\right)^2$ | $\left(\frac{I_n}{I_e}\right)^2$ | $\left(\frac{I_{av}}{I}\right)^2_n$ |
| 1 | 0.811 | 0.852 | 0.998 |
| 3 | 0.087 | 0.091 | 0.983 |
| 5 | 0.029 | 0.030 | 0.953 |
| 7 | 0.013 | 0.014 | 0.911 |
| 9 | 0.007 | 0.007 | 0.855 |
| 11 | 0.004 | 0.004 | 0.787 |
| 13 | 0.002 | 0.002 | 0.712 |
| 15 | 0.001 | 0.001 | 0.630 |
| | 0.954 | 1.001 | |

The fundamental frequency of armature coil current is $f = 45$ cycles per second. For the $n$th harmonic

$$|\alpha d| = 2 \pi d \sqrt{\frac{2 w f n}{\rho s}}$$

Taking $\rho = 2270$ abohm-cm., corresponding to a temperature of 100 deg. cent., and substituting numerical values, $|\alpha d| = 1.45 \sqrt{n}$.

For the top row of conductors $I_b = I_{av}$ and $\delta = 0$, and the extra loss factor for a given harmonic becomes

$$K_n - 1 = (M_r - 1 + 2 N_r)$$

Table II summarizes the calculation of losses for harmonics up to the fifteenth. This gives a total extra loss of 1.79 times that due to a constant direct current equal in magnitude to the r. m. s. value of the coil current. For the bottom conductors $I_b = 0$, and the extra loss factor reduces to $K_n - 1 = (M_r - 1)$. The total extra loss factor calculated for these conductors is 0.18. The average extra loss factor for the embedded portion of the conductors is 0.93. The ratio of the copper loss in the coil to the loss which would be produced by the same coil current if uniformly distributed over the cross-section of the conductor is:

TABLE II
LOSS FACTOR FOR THE CONDUCTOR

| $n$ | $\alpha d$ | $M_r - 1$ | $N_r$ | $K_n - 1$ | $(K_n - 1)\left(\frac{I_{av}}{I}\right)^2_n$ |
|---|---|---|---|---|---|
| 1 | 1.45 | 0.096 | 0.347 | 0.79 | 0.672 |
| 3 | 2.50 | 0.635 | 2.345 | 5.33 | 0.477 |
| 5 | 3.23 | 1.23 | 4.37 | 9.97 | 0.285 |
| 7 | 3.82 | 1.70 | 5.72 | 13.14 | 0.168 |
| 9 | 4.33 | 2.07 | 6.67 | 15.41 | 0.092 |
| 11 | 4.79 | 2.40 | 7.36 | 17.12 | 0.054 |
| 13 | 5.21 | 2.69 | 7.88 | 18.45 | 0.026 |
| 15 | 5.59 | 2.96 | 8.33 | 19.62 | 0.012 |
| | | | | | 1.786 |

Total extra-loss factor, $K_O$, for the embedded portion of the upper conductors is 1.79.

Since the length of the embedded portion is one-half of the half-coil length the extra-loss factor for the half coil is 0.89.

$$K_{dc} = \frac{\Sigma (K_n - 1)(I_{av})_n^2 L_1 + I_e^2 L_2}{I_e^2 L_2}$$

where:

$(K_n - 1)$ is the $n$th harmonic extra loss factor for the embedded portion of the coil.

$L_1$ is the length of the embedded portion of the coil.

$L_2$ is the length of the coil.

$(I_{av})_n$ and $I_e$ are as previously defined.

In our case the numerical value of this ratio is 1.47. As the armature copper is about equally divided between the slots and the end connections, in which the loss is assumed to be normal, the total extra loss factor for an armature coil is 0.47. That is to say, the copper loss in the coil is 47 per cent greater than would be produced by the same coil current if uniformly distributed over the cross-section of the conductor. The ratio of the copper loss in the coil to that as computed by the standardization rules of the A. I. E. E. is

$$K_{dc}' = \frac{\Sigma (K_n - 1)(I_{av})_n^2 L_1 + I_e^2 L_2}{I_{dc}^2 \left(1 - \frac{\beta}{\pi}\right) L_2}$$

Where $I_{dc}$ is the maximum value of the trapezoidal coil current and it is assumed that the brushes short circuit $\frac{\beta}{\pi}$ of the armature coils.

In our case the numerical value of this ratio is 1.51.

Notice that $K_{dc}' = \dfrac{1 - \frac{2}{3}\frac{\beta}{\pi}}{1 - \frac{\beta}{\pi}} K_{dc}$.

Thus it is seen that the armature copper loss for this machine, is more than 50 per cent greater than the value as computed in the time-honored manner. Obviously, the reduction in the extra losses of such a winding by laminating and transposing the conductors would result in a higher rating and efficiency.

The ratio of the heat generated in the embedded portion of the top conductors to that in the embedded portion of the bottom conductors is $2.79 \div 1.18 = 2.36$. This is probably a more important consideration than the loss factor for the entire winding, as it measures the non-uniformity of heat distribution between the conductors. If this winding were used in an a-c. generator the loss factor for the winding at the same fundamental frequency would be 1.22. Notice that, in this case, the extra loss factor for the commutated current is more than double the extra loss factor for the sinusoidal current.

## Discussion

**M. L. Henderson:** It has been shown that the true copper losses in a d-c. armature with large conductors may be a great deal more than the losses as computed in the time-honored way. It was also brought out that the same principles are applicable to the calculation of losses in a synchronous converter. I should like to discuss this application further.

It has been demonstrated that the loss factor for the conductors of a d-c. armature is greater than for the same conductors if used in an a-c. armature on account of the less uniformity of distribution of the higher harmonic components of the current in the d-c. coil. In a synchronous converter the fundamental component of the direct current in the coil is nearly canceled by the alternating current, but the higher harmonics are still present. Nearly the whole loss, therefore, is due to the harmonics and as the loss factors for them are comparatively high, it follows that the combined total copper-loss factor for a synchronous converter is greater even than for a d-c. machine with the same frequency and conductor dimensions.

As an illustration of this, the copper-loss factors for the armature considered in the latter part of this paper have been computed on the assumption that it is to be used in a six-phase converter operating at unity power factor.

For the conductors in the center of a phase belt, where the fundamental components practically cancel, the loss in the embedded part of the top conductor is 8.6 times as large as it would be if the current distribution were uniform, while the loss in the bottom conductors is nearly doubled.

In the conductors at the edge of a phase belt, where maximum heating is expected, the net fundamental component is a larger proportion of the whole, since the alternating current is not exactly in opposition to the fundamental of the direct current in the coil, but the loss in the top conductor is still 4.4 times as large as if the current were uniformly distributed. Even in the bottom tap conductor there is 50 per cent extra loss. These loss factors are much higher than the ones given for the d-c. armature, which are 2.79 and 1.18 for the top and bottom conductors respectively.

This example is not given as representative of actual converter-design practise, but as a comparison of the loss factors for a-c. machine, d-c. machine, and synchronous converter when the same conductors are used. The relatively greater importance of the consideration of extra copper losses in the converter is evident.

Since a large proportion of the extra loss occurs during the commutating period it increases the effective resistance during that period and helps to produce good commutation. This improvement, however, comes only at the expense of machine rating and efficiency.

**R. H. Park:** A study of the effects of eddy currents in d-c. machines and converters was made by the organization with which I am associated, about four years ago. At that time I happened to be interested in the subject to some extent, and made some curves which show the distribution of current density from the top to the bottom of a top conductor in a d-c. machine. These curves, which are shown in Fig. 1 herewith, are arranged a little differently from the curves given in the paper.

In computing the data I didn't calculate the harmonics in the usual way but rather I used Heaviside's operational calculus, since it seemed to be well adapted to the problem. The curves show the current to be initially uniform all over the slot. After the commutation is 5 per cent of the way through, the current hasn't changed at all from the bottom up to ¾ of the way to the top of the slot, although it has already become positive at the top. Each succeeding curve shows the distribution at a later stage of the process of commutation. For this case, the current distribution is practically uniform after an interval of 4 or 5 times the period of commutation.

When the operational method of calculation is used it is possible, at least in some cases, to obtain a somewhat simpler formula for the losses than that given in the paper.

In the simple case of two conductors per slot, full pitch, and linear commutation, the extra loss factor as calculated by the operational method can be put in the form

$$K_u = K_o\,[9\,g\,(\theta_o) + h\,(\theta_o)]$$
$$K_l = K_o\,[g\,(\theta_o) + h\,(\theta_o)]$$

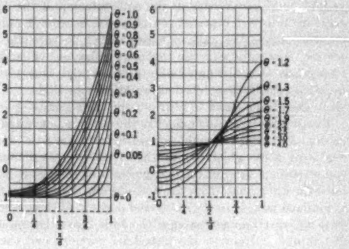

FIG. 1

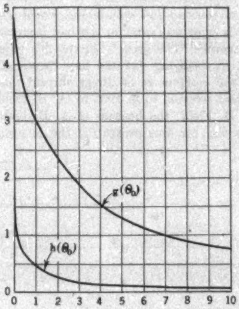

FIG. 2

where, $K_u$ = ratio of extra loss in copper conductor to loss which would exist with a constant d-c. current equal to the maximum value of the trapezoidal coil current.

$K_l$ = same factor for lower conductor.

$$K_o = \frac{8\,w\,d^3\,f}{\rho\,8\,\pi}$$

$$\theta_o = \frac{1}{K_o}\,\frac{\beta}{\pi}$$

$g\,(\theta_o)$ and $h\,(\theta_o)$ are functions of $(\theta_o)$ as shown in Fig. 2 herewith.

**R. F. Franklin:** It has long been recognized that there are eddy current losses in the conductors of d-c. machines and synchronous converters similar to those in a-c. machines, and that due to the trapezoidal current wave introducing numerous harmonics, the relative loss should be greater. Several years ago I made such a mathematical investigation and found this to be the case.

The value in this paper lies not only in giving the method of calculation of this loss, taking into consideration the difference in time of commutation of conductors in the same slot, but also in the presentation of experimental data confirming this theory. Without this experimental confirmation the increase of the eddy-current loss due to the trapezoidal current wave might be questioned.

One of the startling results of this investigation is the large increase of coil resistance during the commutating period. It might be further added that this increase in resistance is accompanied by a decrease in inductance. Such a condition should be advantageous to the commutation of the coil, and if the conductor is laminated or transposed in order to reduce eddy-current losses, the gain in losses might be partially offset by poorer commutation. In my investigation of eddy-current losses, I also investigated this problem and concluded that in most cases the effect on commutation was slight. Experience since then has seemed to bear out this conclusion.

In studying the tests made by the authors, one question arose in my mind which I could not settle from the data given. The exploring wires which are fastened to the copper ribbon measure the resistance drop in the end portions of the coil as well as the imbedded portion. Now the non-uniform distribution of current is confined largely to the imbedded portion, so that the resistance drop measured is an average of the drop due to the non-uniformly distributed current in the imbedded portions and the more or less uniformly distributed current in the end portions. If the length of the end portion is not small compared to the imbedded portion, an appreciable error may be introduced. The close agreement between test and calculations would seem to indicate that either this error was small or else had been considered.

**B. A. Behrend:** The great value of this paper appears to me to lie in its bringing out the importance of current distribution in the conductors of direct current machines. This matter was first referred to in 1905 by A. B. Field and later in 1906 by M. B. Field, the brother of A. B. Field to whom a great debt is due for first presenting the investigation of the phenomena of eddy currents in deep slot-wound conductors. As Mr. Field was associated with me at the time he made his investigation I feel great satisfaction and pride in the value which his work has acquired as the art of designing large machines has progressed. Professor Lyon has done so much to elucidate and elaborate these theories that a paper like the present will once for all dissipate the conception, held by most designers, that the current distribution in the conductors of direct current machines or synchronous converters can be uniform. This is a great service besides the value of the paper with its instructive diagrams and its painstaking calculations including harmonics up to the thirteenth.

As Mr. Park has pointed out, it is possible to attack this subject with the powerful methods of the operational calculus. The electrical engineer must recognize that resistance operators and operational solutions as first propounded by Heaviside forty years ago cannot be ignored much longer. They have come to stay, greatly simplifying the mathematical work and bringing new problems under the scope of the new methods.

The subject is now ripe for a complete review and it is to be hoped that Professor Lyon will give us this and thus bring out the thread which runs so beautifully through all the problems of this nature. Eddy currents in solid slot-wound conductors exhibit in a marked degree the phenomena which occur in solid conductors in air at much higher frequencies. The magnetic field is under control by shaping the slots and, therefore, a great many experimental configurations can be subjected to analysis both experimental and mathematical. By the use of Heaviside resistance operators solutions can be obtained in little time and generalizations effected which are too cumbersome with other methods.

**W. V. Lyon:** In answer to Mr. Franklin's query, I will say that the length of the end turn was approximately 10 per cent of the length of the coil. All of the results have been corrected for this.

# Effect of Transient Conditions
## On Application of D-C. Compound Motors

BY LEON R. LUDWIG[1]
Non-member

***Synopsis.***—*When a d-c. compound motor is started, the rise of current in the series field induces a voltage in the shunt field counter to that applied, and the shunt field current may reach several times normal value in a negative direction. This current reversal gives, in effect, a differentially compounded motor during the starting period and causes the starting torque to be materially reduced. In many applications of compound motors, therefore, predetermined performance is not obtained. In particular cases where the motor is continually started and stopped, the effect may be so serious as to dictate the choice of another type of motor, or one of a special design to minimize the undesirable action.*

*In case the compound motor is disconnected from the line while running, and reconnected with no external resistance, the delay in establishing a flux due to the damping action of the shunt field may permit excessive currents to flow.*

*In other d-c. motors, currents induced in the solid iron portions of the frame and poles exert a damping effect similar to that of the shunt field in the compound motor, which may at times be undesirable. A study of such transients leads to means by which they may be minimized and provides calculation methods for predetermining motor behavior.*

* * * * *

### INTRODUCTION

In the compound motor there are two distinct electrical circuits linked by a common flux. The current changes during transient periods are therefore not inter-dependent, though in most motors the current in the shunt field is dependent largely on the current change in the series field. In the series circuit also, there is an induced voltage which depends on the flux linking the two coils as well as on the speed, which in turn is a function of the flux, series current, and time.

There is, in effect, a third closed electrical circuit consisting of the solid iron portions of the frame and poles, in which eddy currents flow exerting an influence on the main flux.

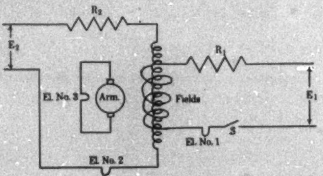

FIG. 1—DIAGRAM OF TEST CIRCUIT

The motor may be started with an initial current in the shunt field or by closing both field circuits simultaneously. In either case the rise of series-field current will induce in both the shunt field and the solid iron a current tending to oppose the establishment of a flux. The induced voltage in the shunt field will be opposite to the impressed voltage and usually will be greater on account of the high transformer ratio between the fields. The shunt field current will usually reverse and restrain the flux from increasing as rapidly as the series current. Under such conditions, the starting torque would be less than with an equivalent straight-series motor.

The oscillogram in Fig. 2 was taken with a compound motor connected as in Fig. 1. The machine was externally driven at constant speed in order to obtain the instantaneous field flux which is directly proportional to the armature voltage. The series current in this case rises inductively to a value limited only by the resistance, and the shunt current reverses, reaching a negative peak of 2.5 times normal. The flux increases very slowly. Another film (Fig. 3) was taken with the shunt field open circuited. An initial current in the

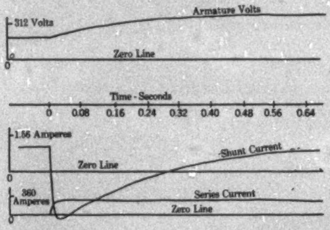

FIG. 2—CURRENT TRANSIENTS OBTAINED FROM TEST

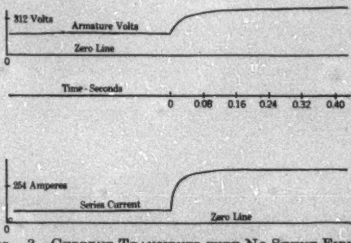

FIG. 3—CURRENT TRANSIENTS WITH NO-SHUNT FIELD

series field gave the same initial flux as in the first test, and this current was increased to the same final value. It will be seen that the flux rise is much more rapid, though it does not increase directly in proportion to the series current because of the solid iron damping.

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[1] Westinghouse Elec. & Mfg. Company, East Pittsburgh, Pa.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., February 13-17, 1928.*

The reduction of starting torque due to the shunt field damping is usually obviated by reducing the starting resistance in series with the motor. This procedure, however, causes the energy required for starting the machine to be increased, and also causes the motor current to reach a higher starting peak. The latter may cause sparking at the commutator and would be undesirable from a standpoint of contactor burning if the motor circuit were opened frequently very soon after the machine was started.

Transients in d-c. machines in general have been dealt with by K. L. Hansen in a paper presented at the Midwinter Convention of the A. I. E. E. in 1917, and though the reversal of the shunt field current was cited in this paper, there was no attempt made at that time to find the exact effect of this reversal on the transient motor characteristic.

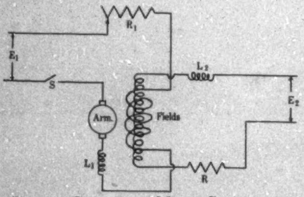

Fig. 4—Diagram of Motor Connections

### ANALYSIS OF TRANSIENT CURRENTS AND FLUX

In compound machines most of the damping is because of the shunt field. It is also possible to take into account the effect of eddy currents in the iron by properly choosing the circuit constants, and the third electrical circuit may therefore be neglected. If $i_1$ is the series current and $i_2$ is the shunt current, the flux will be, neglecting saturation, proportional to a fictitious current ($i$) which is expressed as

$$i = i_1 + a\, i_2$$

in which $a$ is the ratio of the number of shunt field-turns to the series field-turns. The two fundamental equations, referring to Fig. 4, will be:

$$E_1 = M \frac{d\,i}{d\,t} + L_1 \frac{d\,i_1}{d\,t} + R_1\, i_1 + e\, g$$

$$E_2 = a\, M \frac{d\,i}{d\,t} + L_2 \frac{d\,i_2}{d\,t} + R_2\, i_2$$

The generated voltage $e\,g$ must be expressed in terms of instantaneous speed and flux. The constant $M$ is the coefficient of mutual inductance. $L$ is the inductance due to the leakage flux linking the series field, plus the armature inductance, and $L_2$ is the leakage inductance of the shunt field plus any external inductance.

The solution of these equations is given in the appendix (Equations I and II). In Fig. 5 the curves are plotted for the two currents, flux, and torque, assuming that the motor is started with an initial shunt field. As shown by the curves, four-tenths of a second elapses before the shunt field ceases to handicap the series field. It is interesting to note that as the series current decreases when a counter e. m. f. is established, it causes the shunt current to become greater than normal in a positive direction.

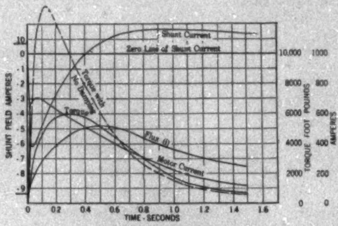

Fig. 5—Calculated Transient Curves with Motor Starting

From these curves it is evident that a very short time elapses before the currents reach their peak values. Since the magnitude of the damping is largely a function of these peak values, it is usually sufficient to obtain only the very early part of the transient in order to determine the effect of damping. The armature of the motor will not begin to rotate until after the current peaks are passed. It is, therefore, often convenient to assume that the motor is blocked and that $e\,g$ in the equation is zero. A solution under this condition is given in the appendix (Equations III and IV). The curves are plotted in Fig. 6, and compare with the test of Fig. 2, except that armature inductance

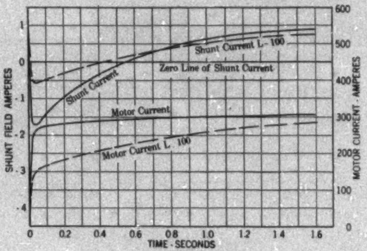

Fig. 6—Calculated Transient Curves with Motor Blocked

was not in the circuit during the test. Furthermore, the effect of saturation was neglected in the calculations.

In case the motor is running and the circuit is opened and then closed before the speed has dropped appreciably, the term $e\,g$ is a function of flux only. Equations (V and VI) in the appendix give this solution, and in Fig. 7 the curves are plotted. It was assumed that the shunt and motor circuits were both opened and closed, or that no initial flux was present. In previous solutions the transients were non-oscillatory; that is, there was no periodic pulsation of current. Under the present conditions, however, the constants must nearly always be such that the final solution contains sine and cosine terms. The phenomenon therefore resembles a condenser charge.

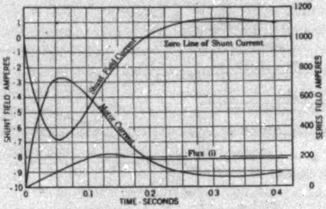

Fig. 7—Calculated Transient Curves with Motor Running and Circuit Closed

The load on the motor was assumed to be such that 100 amperes were required under steady-state conditions. The curve of series current during the oscillation decreases below 100 amperes, later regaining this value. The shunt current, also, oscillates past the steady-state value. The time for one cycle of the oscillation is about the same as that required for the transient to disappear.

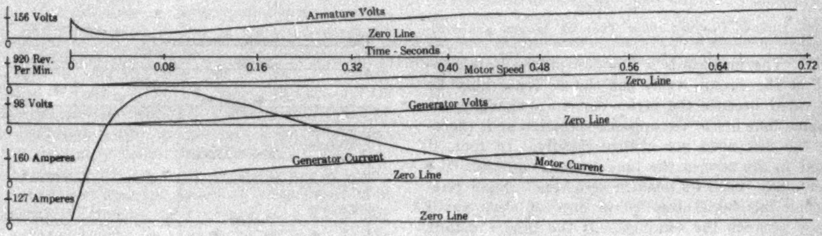

Fig. 8—Oscillogram of Motor-Starting Transients

## Results of Current Transients

In order to find the quantitative reduction in starting torque resulting from the transients described, the curves in Fig. 5 may be compared with curves obtained from an ideally perfect case. This ideal case may be represented by a compound motor in which it is assumed that there is no inter-action between the two fields. The shunt field current will remain constant at its initial value during the transient, if such an assumption is made. The fundamental voltage equation for the series circuit then becomes:

$$E_1 = L\frac{d\,i_1}{d\,t} + R_1\,i_1 + e\,g \qquad \text{(C)}$$

In this equation, $L$ is the sum of $L_1$ and $M$. The curves of torque and current resulting from its solution (Equation (VII), Appendix) are also plotted in Fig. 5. The maximum torque is more than twice as great as that obtained with damping. The average value of torque during the starting period, with damping, is 3250 ft-lb., and without damping, is 4600 ft-lb., or the reversal of the shunt field current causes the torque to be decreased to 71 per cent of its value. The iron would saturate during the current peak, however, and the true torque would be less than 4600 ft-lb. if there were no field interaction.

If it were not necessary to increase starting torque by reducing field inter-action, but rather to decrease the current peak and starting energy, additional starting resistance could be inserted in the ideal motor circuit and the same average torque could be obtained with 71 per cent of the average starting current. The starting loss would be decreased as the first power of the current because additional resistance had been added, and the average starting power could be reduced to 71 per cent.

Fig. 8 is an oscillogram taken as a compound motor was started with a shunt generator for load. The curves in Fig. 9 are an analysis of this oscillogram showing how the total input power is divided in the motor. The accelerating power was calculated from the moment of inertia and instantaneous speed. The losses due directly to field inter-action are included in the load loss curve. Actually, the additional current necessary to provide a given starting torque with a weakened field, gives rise to additional and unnecessary copper loss. The curve of "essential input" is the sum of the actual required power, and the area between the two input curves is the loss which may be charged to field inter-action. This loss is within the motor itself and does not include the additional loss incurred in the starting resistance because of field interaction.

The peak of starting current is a function of generated voltage at the time of the peak. With no field inter-action, and consequently a higher flux, this peak will be reduced at the same time the starting torque is increased.

### Methods of Reducing Field Inter-Action

The damping action of the shunt field in magnitude is proportional to the area traced by the curve of shunt current during its decrease, and this in turn is somewhat proportional to its lowest peak. There are three methods of reducing this area:

1. Altering the time constant of the shunt circuit.
2. Placing resistance in the series circuit.
3. Changing design constants.

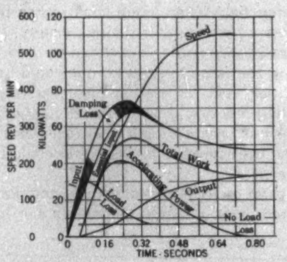

Fig. 9—Curves Plotted from Test of Motor Starting

A study of the curve of shunt current in Fig. 6 shows that the current decreases very rapidly and increases slowly. The increase is a function of the time constant of the circuit itself, but the decrease may be very rapid because the series current is changing at the same time but in the opposite direction and, therefore, the flux need not change rapidly. In fact, if $L_1$ and $L_2$ are zero in the fundamental equation, the current may reach its peak in zero time. Such phenomenon has been observed in case of very small leakage between the windings. If the time constant were increased, as by placing the field coils in parallel rather than in series, the shunt current would regain normal value more rapidly, thereby increasing the flux more rapidly. At the same time, however, the current peak is increased in a negative direction and the traced area will be larger than before.

If, on the contrary, inductance is added to the shunt field circuit, the negative peak is decreased and the area will be less. In Fig. 6, curves are plotted for the currents and flux, with a large inductance in the shunt circuit. These may be compared with the other curves in the same figure, in which $L_2$ was 10 henrys. It will be seen that the peak is reduced from 1.7 amperes to 0.5 ampere.

The oscillogram in Fig. 10 was taken with the field coils in parallel and may be compared with Fig. 2. It will be seen that the negative peak has been increased and the area increased even though the current regains steady state more rapidly.

Equation (VIII) in the appendix, which is a simplification of Equation III if the self-inductive coefficients are zero, states that the negative peak of shunt current depends directly on the resistance of the series circuit. Therefore, if the starting resistance is increased the field inter-action is decreased, and within limits the starting torque will remain materially unchanged. In Fig. 11 it will be seen that the series current is less than in Fig. 2 because of additional resistance, and that the negative peak is somewhat reduced.

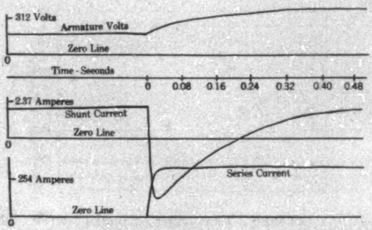

Fig. 10—Current Transients with Shunt Coils in Parallel

The design of the motor may be changed by altering the relative copper on the two fields. The worst condition is an equal division. Equation (8) also shows the inter-action to be a function of the turns ratio; and that if more turns were placed on the shunt field and a smaller current were carried by the coils, transient conditions may be improved. It is not always feasible to make such changes, however, and in such cases another type of motor is the best solution. This, though, would rarely ever be necessary.

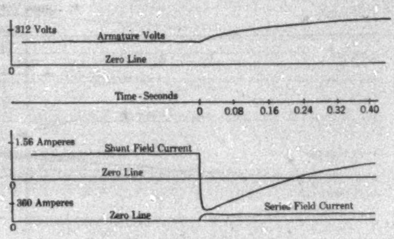

Fig. 11—Current Transients with Increased Starting Resistance

### CONCLUSIONS

It is obvious from the preceding discussion that with many applications of compound motors, the action of the shunt field has no particular disadvantage. It is only in case the starting torque must be all that the motor could possibly supply, or in case the motor is constantly started and stopped, that such phenomena become important.

In case there is doubt as to whether or not the transient conditions will influence compound motor behavior Equations (3) and (4) in the appendix may be used with good accuracy to calculate the initial transient. The effect of saturation should be taken into account, and it may be obtained by first finding the relation of $i$ and time, then plotting the flux against time by the use of a saturation curve of the particular motor involved and the curve of $i$. The resulting curve of flux and time will be somewhat in error because saturation is still neglected in finding the transients of $i_1$ and $i_2$.

In case the shunt field current reverses appreciably, and the flux rise is much slower then it would be neglecting field inter-action, (even though saturation is also taken into account in finding the flux rise in case there was no field inter-action), it is probable that the application would be best fulfilled by a straight series or shunt motor. In the event that a compound motor is desirable, however, for other reasons, the design may be altered by changing the relative amount of copper in the two fields until field inter-action as calculated by Equations (3) and (4) is sufficiently reduced to give satisfactory operation.

In drawing general conclusions from the above, it must be remembered that there are many types of motors so-called compound, including those which have only a small series or shunt stabilizing winding. Because field inter-action is most severe with an equal division of copper in the two fields, this latter group of motors is only slightly affected by the described phenomena. In case of true compound motors, which derive a large portion of their flux from both fields, the general conclusion is that on account of their peculiar transients, they must be applied with care.

Also, because of the variation in magnitude of starting resistance used with the motor, it is not possible to state definite conclusions with regard to a particular motor, without taking into account the exact application conditions. The contents of this paper may therefore serve to aid in checking doubtful applications and in making more clear the general phenomena of compound field inter-action.

## Appendix

### EQUATIONS FOR MOTOR STARTING

The fundamental equations for obtaining compound motor transients are (from Fig. 4):

$$E_1 = M\frac{d\,i}{d\,t} + L_1\frac{d\,i_1}{d\,t} + R_1 i_1 + e\,g \qquad (1)$$

$$E_2 = a\,M\frac{d\,i}{d\,t} + L_2\frac{d\,i_2}{d\,t} + R_2 i_2 \qquad (2)$$

$$i = i_1 + a\,i_2 \qquad (3)$$

If the motor is to be started, the speed and flux will vary with time, and therefore:

$$e\,g = k\,\phi\,s \qquad (4)$$

in which $s$ and $\phi$ are instantaneous values of speed and flux. The instantaneous speed is

$$S = \int_0^t \alpha\,d\,t \qquad (5)$$

in which $\alpha$ is the angular acceleration.

Then $$\alpha = \frac{T\,a}{I} \qquad (6)$$

($T\,a$) is the accelerating torque and equals the total torque produced by the motor minus the counter or load torque. The accelerating torque is usually large as compared with the counter torque, and the latter may be neglected during the transient.

Then $$\alpha = \frac{k_1\,\phi\,i_1}{I} \qquad (7)$$

in which $I$ is the moment of inertia.
Combining Equations (4), (5), (6), and (7) gives:

$$e\,g = k\,\phi\int_0^t \frac{k_1\,\phi\,i_1}{I}\,d\,t \qquad (8)$$

If saturation is not taken into account, $\phi$ is proportional to $i$ and may be replaced by this fictitious current times a constant.

Equations (1) and (2) are very difficult to solve if $e\,g$ is replaced by Equation (8), but it may be assumed in Equation (8) that the flux, which does not vary a great deal if the motor is started with an initial field, is constant. The average value of the flux may be used. Equation (8) therefore becomes:

$$e\,g = K\int_0^t i_1\,d\,t \qquad (9)$$

and (1) and (2) are then:

$$E_1 = M\frac{d\,i}{d\,t} + L_1\frac{d\,i_1}{d\,t} + R_1 i_1 + K\int_0^t i_1\,d\,t \qquad (10)$$

$$E_2 = a\,M\frac{d\,i}{d\,t} + L_2\frac{d\,i_2}{d\,t} + R_2 i_2 \qquad (11)$$

The solution may be obtained easily by use of the Heaviside Expansion Theorem. (See "Heaviside's Operators in Engineering and Physics," by Ernst Julius Berg in the "*Journal* of the Franklin Institute," November, 1924.)

Letting $p$ be the operator $\frac{d}{d\,t}$ and $\frac{1}{p}$ be the operator $\int d\,t$ under Heaviside conditions, and from the relation

$$\frac{d\,i}{d\,t} = \frac{d\,i_1}{d} + a\,\frac{d\,i_2}{d\,t}$$

Equations (**10**) and (**11**) may be rewritten:

$$E_1 = a\,M\,p\,i_2 + \left(M\,p + L_1\,p + \frac{k_1}{p} + R_1\right) i_1$$

$$= b\,i_2 + A_1\,i_1 \qquad (\mathbf{12})$$

$$E_2 = a\,M\,p\,i_1 + (a^2\,M\,p + L_2\,p + R_2)\,i_2$$

$$= b\,i_1 + A_2\,i_2 \qquad (\mathbf{13})$$

Let $E_2 = 0$ to find the equation for the transients of $i_2$, then the steady state term $\frac{E_2}{R_2}$ may be added for the complete solution.

From (**13**) and (**12**)

$$i_1 = -\frac{A_2}{b}\,i_2 \qquad E_1 = b\,i_2 - \frac{A_1\,A_2\,i_2}{b}$$

$$i_2 = \frac{E_1\,b}{b^2 - A_1\,A_2}$$

Replacing the three constants by their values and simplifying,

$$i_2 = -E_1\,\frac{a\,M\,p^2}{F\,p^3 + G\,p^2 + H\,p + K\,R_2} = \frac{Y\,(p)}{Z\,(p)} \qquad (\mathbf{14})$$

where $F = (a^2\,M\,L_1 + L_2\,M + L_1\,L_2)$

$G = (a^2\,M\,R_1 + R_1\,L_2 + R_2\,M + R_2\,L_1)$

$H = (R_1\,R_2 + a^2\,M\,K + L_2\,K)$

Equation (**14**) is termed the operational solution, and it may be transformed into an algebraic solution by means of the Expansion Theorem, the form of which is:

$$i_2 = -E_1\left[\frac{Y_0}{Z_0} + \sum \frac{Y_p\,\epsilon^{pt}}{p\,\dfrac{d\,Z}{d\,p}} \quad . \quad . \quad . \quad . \quad . \right]$$

$$p = p_1, p_2 \ldots$$

The roots $p_1$, $p_2$, and $p_3$ may be obtained by solving $Z\,(p)$, the denominator of (**14**) for $p$.

The term $\frac{Y\,o}{Z\,o}$ is the steady state solution and in this case, with zero substituted for $p$ in (**14**), is zero. The final result obtained by substituting in the Expansion Theorem is:

$$i_2 = \frac{E_2}{R_2} - E_1\left[\frac{a\,M\,p_1\,\epsilon^{p_1 t}}{3\,F\,p_1^2 + 2\,G\,p_1 + H} + \frac{a\,M\,p_2\,\epsilon^{p_2 t}}{3\,F\,p_2^2 + 2\,G\,p_2 + H} + \frac{a\,M\,p_3\,\epsilon^{p_3 t}}{3\,F\,p_3^2 + 2\,G\,p_3 + H}\right] \qquad (\mathbf{I})$$

In this equation the steady state term has been added.

To find $i_1$, solve for $i_2$ in (**13**); substitute the term for $i_2$ in (**12**) and solve (**12**) for $i_1$. From this operational solution, the complete solution may be obtained as before, and is:

$$i_1 = E_1\left[\frac{[(a^2\,M + L_2)\,p_1 + R_2]\,\epsilon^{p_1 t}}{3\,F\,p_1^2 + 2\,G\,p_1 + H} + \frac{[(a^2\,M + L_2)\,p_2 + R_2]\,\epsilon^{p_2 t}}{3\,F\,p_2^2 + 2\,G\,p_2 + H} + \frac{[(a^2\,M + L_2)\,p_3 + R_2]\,\epsilon^{p_3 t}}{3\,F\,p_3^2 + 2\,G\,p_3 + H}\right] \qquad (\mathbf{II})$$

The curves plotted in Fig. 5 were from the numerical evaluation of these equations in case of starting a 70-hp. compound motor with an external resistance of 0.32 ohm. The ratio of series field ampere-turns to shunt field ampere-turns is 2.5. The constants of the motor are:

$R_1 = 0.378$ $\qquad a = 88$

$R_2 = 0336.0$ $\qquad K = 0.5$

$E_1 = 310$

$E_2 = 230$ $\qquad$ Then $F = 0.635$

$M = 0.012$ $\qquad G = 44.5$

$L_1 = 0.005$ $\qquad H = 177.5$

$L_2 = 10$

The cubic equation for $Z\,(p)$ is

$$0.635p^3 + 44.5\,p^2 + 177.5\,p + 160 = 0$$

The three roots are:

$$p_1 = -\,65.7 \qquad p_2 = -\,2.7 \qquad p_3 = -\,1.45$$

Equations (**1**) and (**2**) become:

$$i_2 = 0.685 + 8.5\,\epsilon^{-65.7t} - 18\,\epsilon^{-2.7t} + 9.5\,\epsilon^{-1.45t}$$

$$i_1 = -\,770\,\epsilon^{-65.7t} - 350\,\epsilon^{-2.7t} + 1120\,\epsilon^{1.45t}$$

### EQUATIONS FOR MOTOR BLOCKED

In case the motor is blocked, $e\,g$ is zero and equations (**12**) and (**13**) become:

$$E_1 = i_1\,(R_1 + p\,L_1 + p\,M) + a\,M\,p\,i_2 \qquad (\mathbf{15})$$

$$E_2 = i\,(R_2 + p\,L_2 + a^2\,p\,M) + a\,M\,p\,i_1 \qquad (\mathbf{16})$$

$E_2$ may be called zero as before if the motor is started with an initial field.

The two operational solutions are:

$$i_2 = \frac{-\,E_1\,(a\,M\,p)}{F\,p^2 + G\,p + R_1\,R_2} \qquad (\mathbf{17})$$

$$i_1 = \frac{E_1\,(r + p\,L_2 + p\,a^2\,M)}{F\,p^2 + G\,p + R_1\,R_2} \qquad (\mathbf{18})$$

in which $F = (L_1\,L_2 + L_2\,M + a^2\,M\,L_1)$

$G = (R_2\,L_1 + R_2\,M + L_2\,R_1 + R_1\,a^2\,M)$

In this case $Z\,(p)$ is a quadratic and the algebraic roots may easily be found.

The complete solutions are then:

$$i_2 = \frac{E_2}{R_2} - \frac{E_1\,a\,M}{\sqrt{G^2 - 4\,F\,R_1\,R_2}}\left[\epsilon^{\sqrt{\frac{G^2}{4F^2} - \frac{R_1\,R_2}{F}}\,t}\right.$$

$$- \epsilon^{-\sqrt{\frac{G^2}{F^2F} - \frac{R_1 R_2}{4}}\,t}\Bigg]\,\epsilon^{-\frac{Gt}{2F}} \qquad \text{(III)}$$

$$i_1 = \frac{E_1}{R_1} + E_1 \Bigg[\Bigg(\frac{2\,F\,R_2}{G^2 - G\sqrt{G^2 - 4\,F\,R_1\,R_2} - 4\,F\,R_1\,R_2}$$

$$+ \frac{L_2 + a^2 M}{\sqrt{G^2 - 4\,F\,R_1\,R_2}}\Bigg)\,\epsilon^{\sqrt{\frac{G^2}{4F^2} - \frac{R_1 R_2}{F}}\,t}$$

$$+ \Bigg(\frac{2\,F\,R_2}{G^2 + G\sqrt{G^2 - 4\,F\,R_1\,R_2} - 4\,F\,R_1\,R_2}$$

$$- \frac{L_2 + a^2 M}{\sqrt{G^2 - 4\,F\,R_1\,R_2}}\Bigg)\,\epsilon^{-\sqrt{\frac{G^2}{4F^2} - \frac{R_1 R_2}{F}}\,t}\Bigg]\,\epsilon^{-\frac{Gt}{2F}} \qquad \text{(IV)}$$

These equations were evaluated for the starting of the same motor but with different voltages and resistances. The changes are:

$$E_1 = E_2 = 230$$
$$R_2 = 230$$
$$R_1 = 0.75$$

If $L_2 = 10$,

$$i_1 = 307 - 40\,\epsilon^{-2.1t} - 267\,\epsilon^{-102.7t}$$
$$i_2 = 1 - 3\,\epsilon^{-2.1t} + 3\,\epsilon^{-102.7t}$$

If $L_2 = 100$,

$$i_1 = 306 - 160\,\epsilon^{-1.2t} - 146\,\epsilon^{-130t}$$
$$i_2 = 1 - 1.65\,\epsilon^{-1.2t} + 1.65\,\epsilon^{-130t}$$

An approximate solution will be obtained with the motor blocked for the purpose of showing the dependence of field interaction on certain factors. The fundamental equations might be written, neglecting leakage inductance,

$$E_1 = M\,\frac{d\,i}{d\,t} + R_1\,i_1 \qquad (19)$$

$$E_2 = a\,M\,\frac{d\,i}{d\,t} + R_2\,i_2 \qquad (20)$$

These equations may be rewritten in terms of $i$.

$$\left(\frac{a^2 R_1 M + R_2 M}{R_2}\right)\frac{d\,i}{d\,t} + R_1\,i$$

$$= \left(\frac{R_2 E_1 + a\,R_1 E_2}{r}\right) = K\,\frac{d\,i}{d\,t} + R_1\,i = b \qquad (21)$$

The solution is known to be:

$$i = \frac{b}{R_1}\left(1 - A\,\epsilon^{-\frac{R_1 t}{K}}\right) \qquad (22)$$

in which $A$ is an arbitrary constant. If an initial field is present, when $t = 0$

$$i = \frac{a\,E_2}{R_2}$$

and (**22**) becomes

$$i = \frac{b}{R_1} - \left(\frac{b}{R_1} - \frac{a\,E_2}{R_2}\right)\epsilon^{-\frac{R_1 t}{K}} \qquad (23)$$

This equation may be differentiated and substituted in (**20**), from which

$$i_2 = \frac{E_2}{R_2} - \frac{a\,E_1}{a^2 R_1 + R_2}\,\epsilon^{-\frac{R_1 t}{K}} \qquad (24)$$

The maximum negative peak occurs when $t = 0$, and is therefore

$$i_2\,(\text{max.}) = \frac{E_2}{R_2} - \frac{a\,E_1}{a^2 R_1 + R_2} \qquad \text{(VIII)}$$

$R_2$ is small compared to $a^2 R_1$, so that, approximately,

$$i_2\,(\text{max.}) = \frac{E_2}{R_2} - \frac{E_1}{a\,R_1} \qquad (25)$$

This equation shows that the negative current peak depends on the primary voltage and resistance and the turns ratio.

## EQUATIONS FOR MOTOR RUNNING

In case the switch is closed with the motor running at normal speed, the expression for $e\,g$ becomes:

$$e\,g = K\,\phi$$

and it is not necessary to make any assumptions. The voltage equations become then:

$$E_1 = (p\,L_1 + p\,M + R_1 + K)\,i_1 + (M\,a\,p + K\,a)\,i_2 \qquad (26)$$

$$E_2 = a\,M\,p\,i_1 + (p\,L_2 + a^2 M\,p + R_2)\,i_2 \qquad (27)$$

If the shunt field has no initial current but a voltage is impressed on both circuits simultaneously, the solution may be obtained by solving for $i_1$ and $i_2$ with $E_2 = 0$, repeating with $E_1 = 0$, and adding the two solutions to obtain the complete one. The operational solutions are:

$$i_2 = \frac{-E_1\,a\,M\,p}{F\,p^2 + G\,p + H} \qquad (28)$$

$$i_1 = E_1\,\frac{(p\,L_2 + a^2 M\,p + R_2)}{F\,p^2 + G\,p + H} \qquad (29)$$

when $E_2 = 0$, and are

$$i_2 = E_2\left(\frac{p\,L_1 + p\,M + R_1 + K}{F\,p^2 + G\,p + H}\right) \qquad (30)$$

$$i_1 = -E\left(\frac{p\,a\,M + K\,a}{p^2 F + G\,p + H}\right) \qquad (31)$$

when $E_1 = 0$

$F = (L_1 L_2 + L_2 M + a^2 L_1 M)$
$G = (L_2 R_1 + L_2 K + a^2 M R_1 + L_1 R_2 + M R_2)$
$H = (R_1 R_2 + R_2 K)$

Solving $Z\ (p)$ for $p$ gives:

$$p = \frac{-F}{2G} \pm \sqrt{\frac{F^2}{4G^2} - \frac{H}{F}}$$

In most cases $\frac{H}{F} > \frac{F^2}{4G^2}$ and $p_1$ and $p_2$ must be expressed as

$$p_1 = -\alpha + j\,B$$
$$p_2 = -\alpha - j\,B$$

Equation (**28**) placed in the expansion becomes

$$i_2 = \frac{-2\,E_1\,a\,M}{\sqrt{4\,H\,F - G^2}} \sin\sqrt{\frac{H}{F} - \frac{G^2}{4\,F^2}}\,t\,\epsilon^{-\frac{Gt}{2F}} \tag{32}$$

This equation forms a part of the complete solution, the remaining part being obtained from (**30**).

The entire solution for $i_2$ is:

$$i_2 = \frac{E\,(R_1 + K)}{R_1\,R_2 + R_2\,K} - 2\,E\left[\frac{2\,F\,Q + G\,(L_1 + M)}{4\,F^2\,B^2 + G^2}\cos B\,t + \frac{a\,M}{\sqrt{4\,H\,F - G^2}}\sin B\,t + \frac{G\,Q - 2\,F\,B^2\,(L_1 + M)}{4\,F^2\,B^3 + G^2\,B}\sin B\,t\right]\epsilon^{-\frac{Gt}{2F}} \tag{V}$$

in which $Q = (R_1 + K - L_1 - M)$ and $E_1 = E_2$. The entire solution for $i_1$ obtained from (**29**) and (**31**) is likewise:

$$i_1 = \frac{E\,(R + K\,a)}{R_1\,R_2 + K\,R_2} - 2\,E\left(\frac{2\,F\,P + G\,S}{4\,F^2\,B^2 + G^2}\cos B\,t + \frac{G\,P - 2\,F\,B^2\,S}{4\,F^2\,B^3 + G^2\,B}\sin B\,t\right)\epsilon^{-\frac{Gt}{2F}} \tag{VI}$$

in which

$$P = (R_2 + K\,a - L_2 - a^2\,M - M)$$
$$S = (a\,M + L_2 + a^2\,M)$$

Assuming that $K$ is 1.2, the steady-state motor current will be 100 amperes. Also, $R_1 = 0.058$ $E_1 = E_2 = 230$ $R_2 = 230$. The above equations were evaluated by supplying the other constants for the same motor with the results:

$$i_2 = 1 - (\cos 13\,t + 24.5 \sin 13\,t)\,\epsilon^{-14.2\,t}$$

$$i_1 = 100 + (-100 \cos 13\,t + 2223 \sin 13\,t)\,\epsilon^{-14.2\,t}$$

### EQUATIONS WITH NO DAMPING

To obtain a solution for the ideally perfect case of no damping, the fundamental equation is:

$$E_1 = \frac{L\,d\,i_1}{d\,t} + R_1\,i_1 + K\int_0^t i_1\,d\,t$$

It will be assumed that the motor is starting with an initial field. The operational solution is:

$$E_1 = \left(R_1 + L\,p + \frac{K}{p}\right)i_1$$

and the complete solution is:

$$i_1 = E_1\left[\frac{2\,L\,\epsilon^{\sqrt{\frac{R_1^2}{4L^2} - \frac{K}{L}}\,t}}{\sqrt{R_1^2 - 4\,K\,L} - R_1} + \frac{2\,L\,\epsilon^{-\sqrt{\frac{R_1^2}{4L^2} - \frac{K}{L}}}}{-\sqrt{R_1^2 - 4\,K\,L} - R_1}\right]\epsilon^{-\frac{Rt}{2L}} \tag{VII}$$

If the same constants are used as those in the first part of the appendix, except that $L = L_1 + M$,

$$i_1 = 950\,\epsilon^{-1.4\,t} - 950\,\epsilon^{-20.6\,t}$$
$$i_2 = 0.685$$

Throughout all the above equations, the action of the eddy currents in the solid iron may be taken into account approximately by using a fictitious value of $M$. The action of the eddy currents is to permit more rapid current changes than would otherwise be possible, which means that $M$ must be reduced. The proper value may be found experimentally by taking with an oscillograph the rise of current in either field with the other field open circuited. The value of inductance calculated from a curve thus obtained will be low even if the iron does not saturate, and this value used in the equations will approximate the eddy current damping.

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## Discussion

**R. F. Franklin:** There is one important point which Mr. Ludwig has not discussed. The effect of the induced shunt-field current in retarding the flux build-up and reducing the motor starting torque has been ably treated; the effect on commutation, another important consideration, has been neglected. During transient conditions, commutation is affected by both the magnitude of the armature current and the rate of flux change in the motor. For various reasons, enumerated by the author, it is desirable to keep the starting current a minimum, and from a commutation point of view this is desirable also. However, with regard to the flux change, for high torque it is desirable to allow the flux to increase as rapidly as possible, but for best commutating conditions the flux should change only slowly. And so we have two operating conditions which require conflicting features of design and in the consideration of one the other cannot be neglected.

**L. R. Ludwig:** It must be remembered that there are two applications, in one sense of the word, for compound motors. The limitation to be met in one of these cases is the torque, and severe applications may dictate maximum possible starting output. It is in such cases as these that the elimination, as far as possible, of field interaction will lead to better compound-motor performance.

If, on the other hand, the application is such that commutation is a limit, then if it is possible to reduce field interaction, and, therefore, to insert additional starting resistance in series with the motor, and by this means decrease the peak value of current, commutation can certainly be aided. The changes in field flux in cases with which the paper deals, are so slow (see Fig. 2) that increasing this flux more rapidly will increase the voltage induced in the short-circuited coils by transformer action, to a very small extent. That is, the effect on commutation of more rapid acceleration can be neglected because the decrease of peak armature currents has a much greater beneficial effect on commutation than the more rapid flux change has harmful effect.

# Loudspeakers of High Efficiency
## and Load Capacity

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Associate, A. I. E. E.

***Synopsis.**—The design of high quality horn-type loudspeakers with moving coil drivers is considered. Efficiency and maximum output capacity obtainable from this type of loudspeaker are calculated. Methods of providing load capacity greater than that possible with a single loudspeaker are described.*

* * * * *

### I. Introduction

Two very desirable properties in loudspeakers besides fidelity of reproduction, are high efficiency and high output capacity. Efficiency is desirable not because power from the source (light socket or batteries) is costly, but because it means that a smaller power amplifier may be used. This greatly decreases the first cost and also the cost of maintenance. In the case of auditorium loudspeakers, high output capacity from the amplifier is obtained usually by the use of high plate potentials. For this reason, it is desirable to make it possible to use amplifiers of smaller rating with consequent lower voltages so that inexperienced operators may readily maintain them. In the case of a home loudspeaker, this is even more desirable.

High output capacity, of course, is more necessary for auditorium loudspeakers than for home loudspeakers. The average small loudspeaker, however, is not capable of radiating sufficient sound without overload when certain kinds of music are being reproduced even for the home.

In the early days of loudspeaker development, loudness and fidelity in reproduction were thought to be incompatible. As time went on, some workers began to reason that perhaps by sacrificing efficiency, the fidelity of reproduction at reasonable volumes could be improved. So, by heavy damping or by the use of vibrating systems in which inertia played the principal role, they made devices which were more faithful in reproducing sounds, but were less efficient than the preceding highly resonant loudspeakers. The success of these developments led many to believe that high efficiency and high quality were not to be found together in loudspeaking devices.

The purpose of this paper is to describe a high quality loudspeaker, the efficiency of which is many times that of the conventional type and of very large load capacity. The author is indebted to many other workers in this field for the great wealth of information that has been made available in recent years† through publications.

The new device combines the excellent radiating properties of the slowly expanding exponential horn having a large mouth[1] with the good electromechanical coupling of the electrodynamic or moving coil motor element. Both of these make for high efficiency. They also make for great load capacity, for with a good radiating system, the diaphragm may be small and the motion of the diaphragm slight, making it fairly easy to prevent rattling; and with a moving coil drive, the force does not vary with displacement, eliminating a source of non-linearity common to moving iron types of drivers. It is likely that no other combination of radiating system and motor element has such possibilities of efficiency and load capacity.

### II. Description and Design of the Loudspeaker

*a. The Horn.* Before considering efficiency and load capacity, the design of a system which responds uniformly to a broad band of frequencies must be dealt with. It is well known that the exponential horn is a uniform radiator of sound for a given air velocity at its throat for all frequencies, from the highest down to a certain critical or cut-off frequency determined by the rate of expansion of the horn section.[1] If the equation of the horn is

$$A = A_o \, \epsilon^{Bx} \tag{1}$$

the cut-off frequency is given by the relation

$$f = \frac{B\,a}{4\,\pi} \tag{2}$$

where $a$ is the velocity of sound in air. If cm. units are used for $x$, $a$ should be in centimeters per sec. or 34,400. Above this critical frequency, the radiation resistance at the throat of the horn rapidly approaches a constant value of

$$r = \rho\, a\, A_o \tag{3}$$

where $\rho$ is the density of air. The value of $\rho\, a$ is 41.2, this figure representing the mechanical impedance density in dynes/(cm./sec.), (or mechanical ohms) per sq. cm. of area at the throat of the horn. To attach some physical significance to this figure, a throat of one sq. cm. section, having for its mechanical impedance 41.2 ohms, will radiate 41.2 ergs per second of sound power when the velocity of air at its throat is one cm. per second. This relation, of course, is exactly analogous to the electric case of a resistance of 41.2 ohms

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†For all references see Bibliography.

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which would dissipate the same number of watts for a current of one ampere.

The relation given above assumes that the horn is extended to a large area at the mouth so as to transmit the sound energy effectively to the atmosphere. In the paper to which reference is made, it was suggested that the diameter of the mouth (if of circular section) be

$$D = \frac{4}{B} \tag{4}$$

In terms of the wavelength corresponding to the cut-off frequency,

$$D = \frac{\lambda}{\pi} \tag{5}$$

In practise, the mouth may be somewhat smaller without causing serious resonance effects. Horns of sections other than circular should have mouth areas equivalent to the above circle.

The exponential horn is now generally recognized as the superior shape. A recent paper by Ballantine[2] shows that the so-called Bessel horns of the type $A = b\,x^n$ are similar to the exponential horn in their radiation characteristic if $n$ is chosen very large, and a statement is made that, in view of this, the exponential horn loses a great deal of its significance. As a matter of fact, the Bessel horn approaches the exponential horn not only as to radiation characteristic but as to shape as well when $n$ is increased without limit. This fact was shown by the present writer in his discussion of Ballantine's paper.[3] Thus, Ballantine's work in reality gives further evidence of the superiority of the exponential horn.

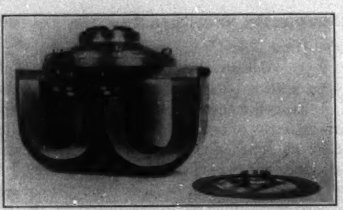

FIG. 1—LOUDSPEAKER ELEMENT

*b. Mechanical Vibrating Systems.* Fig. 1 shows one form of the new loudspeaker elements with the diaphragm placed alongside. Permanent magnets of cobalt steel supply the magnetic field. A piston or a plunger acting diaphragm with a flexible mounting is chosen because it can be made to have only one resonance in the acoustic range of frequencies; *i. e.*, a lumped mass in combination with a lumped compliance has only one resonance. Flat diaphragms as used in the past have a number of resonance frequencies within the acoustic range because such diaphragms cannot act as plungers. To obtain this plunger motion, the central portion of the diaphragm is stiffened by any of a number of methods of corrugation while the edge is made very flexible, either by mounting on an annular ring of rubber or by suitable corrugation of the metal at the periphery. In the diaphragm shown in Fig. 1, the shape is that of seven intersecting cones with a circular bead at the periphery for additional stiffening. Rubber is used for the flexible mounting.

The driving coil may be attached rigidly to the diaphragm, but it is better if an intervening resilient member of the correct stiffness is placed between the coil and diaphragm. In mechanical systems made up principally of masses and a mechanical resistance, better transmission of motion results if spring members are interposed between the separate masses in the chain.[4] This is similar to the electrical case of a telephone cable in which capacity and resistance predominate and in which the transmission characteristic is improved by inserting loading coils at intervals along the line. In the diaphragm shown, six cantilever arms of a metallic spider are inserted between the coil and the diaphragm.

The diaphragm is made, of course, as thin as is consistent with internal rigidity. With most sizes and shapes of corrugated aluminum diaphragms, the thickness must be at least

$$t = 0.00035\,A_d \tag{6}$$

($A_d$ = area of the diaphragm) to insure plunger action and adequate strength. The justification of the constant proportionality between thickness and area is that the fundamental resonance frequency of such diaphragms, considering the edge at rest, will be the same, assuming similar contours for all. This internal resonance must of necessity be above the highest frequency it is desired to reproduce, if the motion of the diaphragm is to be like that of the plunger. A fixed lower limit to this resonance frequency requires that the thickness shall not be less than a certain constant times the area.

If an air chamber transformer is used to step-up the velocity of the air on entering the horn, the mechanical impedance imposed on the diaphragm by the horn will be increased by the square of the transformation ratio

$$r = 41.2\,A_o\left(\frac{A_d}{A_o}\right)^2 = 41.2\,\frac{A_d^2}{A_o} \tag{7}$$

Thus, for a given area of diaphragm, the damping may be varied by varying $A_o$, and the correct value of damping is secured by proper choice of $A_o$[1]. The transformation from the large area of the diaphragm to the small area of the throat cannot be obtained physically without an air space immediately above the diaphragm. As pointed out previously,[1] this space must be small if the air displaced by the diaphragm is to be forced into the horn at the higher frequencies. Some of the volumetric displacement of air by the diaphragm must go to increase the pressure of air in the chamber and therefore this chamber is the equivalent of a mechanical capacity.[4] The stiffness of the air chamber referred to the diaphragm is obtained by considering its reaction on the diaphragm when the throat of the horn is closed. This stiffness, assuming adiabatic changes, is

$$S_2 = \frac{1.4\, A_d^2}{V_o}\, p_o \text{ dynes per cm.}^4 \qquad (8)$$

where $V_o$ is the air chamber volume and $p_o = 1.01 \times 10^6$ dynes per cm.$^2$ or atmospheric pressure.

If the relation between the values of mass of diaphragm, mass of coil, the spring stiffness, air chamber stiffness and radiation damping is properly chosen, it is possible to obtain a device which responds uniformly to all frequencies from the lower cut-off of the horn to an upper cut-off frequency which is determined by the mechanical system itself. The following relations hold for the design if this cut-off frequency is $f_c$

$$s_1 = \pi^2 f_c^2\, m \qquad (9)$$

$$s_2 = 2\, \pi^2 f_c^2\, m \qquad (10)$$

$$r = \pi\, f_c\, m \qquad (11)$$

where $m$ = mass of diaphragm = mass of coil
$s_1$ = stiffness of spider
$s_2$ = stiffness of air chamber
$r$ = radiation damping due to horn.

Having chosen these quantities in this way, the response curve for $f_c = 5000$ will be as in Fig. 2, for a constant driving force $F$ due to current in the moving coil. The equation of this curve is:

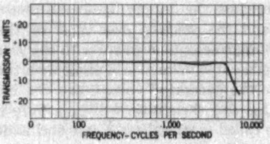

FIG. 2—CALCULATED FREQUENCY RESPONSE

$$W = 10^{-7}\, \frac{F^2}{r}\; \frac{1}{1 + 16\left(\frac{f}{f_c}\right)^4 - 64\left(\frac{f}{f_c}\right)^6 + 64\left(\frac{f}{f_c}\right)^8} \text{ watts} \qquad (12)$$

Over most of the range $W = 10^{-7} \frac{F^2}{r}$. This relation does not take into account the falling off effect at low frequencies caused by the stiffness of the diaphragm supporting member or the cut-off of the horn. Because of the fact that the moving coil-type of drive requires no stabilizing restoring force as does the moving iron type, this edge stiffness may be made as small as desired. In like manner if space permits the use of a large horn, the cut-off frequency of the horn may be made as low as desired.

The application of the foregoing will be made clear if an actual design is considered. Suppose we choose a diaphragm of aluminum 1.7 in. in diameter.

$$A_d = 14.7 \text{ cm.}^2$$

The minimum thickness is

$$t = 0.00035 \text{ by } 14.7 = 0.00508 \text{ cm.} = 0.002 \text{ in.}$$

The mass of this diaphragm is

$$m = 2.7 \text{ by } 14.7 \text{ by } 0.00508 = 0.202 \text{ gms.}$$

Considering that the mass of the prongs of the spider resilient member, through which the coil drives the diaphragm, adds to the effective mass of the diaphragm itself, this mass will be increased to approximately

$$m = 0.230 \text{ gms.}$$

The mass of the coil and coil form together should also be approximately 0.230 grams. By careful design, the mass of the form can be made small, so that a good percentage of the 0.230 grams will be useful conducting material.

The stiffness of the resilient member between the driving coil and the diaphragm for $f_c = 5000$ cycles is $s_1 = \pi^2$ by $5000^2$ by $0.230 = 56.7$ by $10^6$ dynes per cm. This member may be provided by six spokes of a spider, the ends of which are attached to the diaphragm. The spider shown in Fig. 1 is integral with the coil form, the spokes being a continuation of a thin aluminum cylinder. The eddy-current losses in the coil form are negligible for thicknesses of the order of 0.003 in. Each spoke should have 1/6 of the above stiffness or $9.3 \times 10^6$ dynes/cm., the dimensions being determined by the formula

$$s = \frac{E\, w\, t^3}{l^3} \qquad (11)$$

where $E$ is the modulus of elasticity (7 by 10 in. for aluminum), and $w$, $t$, and $l$ are the width, thickness, and length of the spokes. The formula given is for a cantilever free at one end. In the present case, the width and length of the spokes are chosen and the thickness calculated.

$$w = 3/64 \text{ in.} = 0.119 \text{ cm.}$$

$$l = 3/16 \text{ in.} = 0.476 \text{ cm.}$$

From (**12**) $t = 0.476 \sqrt[3]{\frac{9.3 \text{ by } 10^6}{7 \times 10^{11} \text{ by } 0.119}}$

$$= 0.0224 \text{ cm.} = 0.009 \text{ in.}$$

Next in order is the determination of the volume of the air cavity above the diaphragm. Its stiffness is $s_2 = 2\, s_1 = 113.4 \times 10^6$. The volume is determined by equation (**8**)

$$113.4 \text{ by } 10^6 = \frac{1.4 \text{ by } 14.7^2}{V_o} \text{ by } 1.01 \text{ by } 10^6$$

$$V_o = 2.7 \text{ cm.}^3$$

To allow for the annular rubber supporting ring, the diameter of the cavity will be ⅛ in. larger than the metallic part of the diaphragm or approximately 1.825 in. The height of the air cavity is obtained by dividing the volume of the cavity by the area corresponding to this diameter.

$$h = 1.60 \text{ mm., or } 0.063 \text{ in.}$$

A uniform height of cavity is provided, because all parts of the diaphragm move through the same displacement.

The required damping and throat area are determined from equation (**11**)

$r = \pi \times 5000$ by $0.230 = 3620$ dynes per cm. per sec.

Substituting in equation (**7**) $3620 = 41.2 \times \dfrac{14.7^2}{A_o}$ from which $A_o = 2.46 \text{ cm.}^2$

A circle whose diameter is 0.7 in. has this area.

All of the principal dimensions of the loudspeaker element have now been determined. The horn should have an orifice 0.7 in. in diameter and expand slowly enough and have a mouth area large enough to transmit the desired low frequencies. Suppose the required lower cut--off frequency is 100 cycles. From equation (**2**)

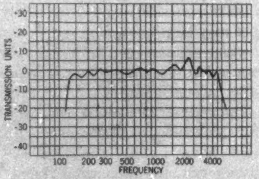

Fig. 3—Experimental Response Curve

$$100 = B \text{ by } \frac{34400}{4\,\pi}$$

$$B = 0.037$$

The equation of the horn is $A = A_o\,\epsilon^{0.037x}$ for cm. units. The mouth of the horn should have a diameter at least equal to one fourth wave length of the lowest frequency or

$$D = \tfrac{1}{4} \text{ by } \frac{34400}{100} = 86 \text{ cm.} = 34 \text{ in.}$$

If the horn is of square section, the mouth area should be equivalent to a circle having the above diameter.

Fig. 3 shows an experimental curve of response against frequencies for the loudspeaker of Fig. 1 when placed on a horn having a 100-cycle cut-off.

## III. Calculation of Efficiency

By efficiency we shall mean the ratio of sound output to electrical input to the moving coil. The power required for field excitation if electromagnets are used will not be considered. The real advantage of high efficiency, as above defined, is that a great saving in amplifier capacity is effected. Although the field excitation power usually amounts to as much or more than the electrical input to the moving coil, it is conveniently obtained. Sufficient power for the voice coil however, is not so easy to obtain.

The calculation of efficiency for the design just given will first be made to illustrate the method, and then the general consideration of efficiency will be taken up. Suppose that the mass of conducting material in the coil may be 0.110 grams, without causing the mass of the coil and coil form to exceed 0.230 grams. A coil consisting of 56 turns of No. 40 copper wire, on a form 0.540 in. in diameter, has this mass, and its resistance is approximately 8 ohms. With small coils, the reactance is not sufficiently great to cause the impedance to be much greater than this for frequencies up to 5000. When a voltage is applied to the coil of such a structure, part of it is consumed in resistance drop and part will be expended in overcoming a generated voltage due to motion of the coil in the magnetic field. A convenient quantity which will be used throughout this discussion of efficiency is known as motional impedance.[8] This impedance is obtained by dividing the generated back voltage by the corresponding current in the coil. In the case of this type of loudspeaker, the velocity of the coil is in phase with the current because the driving force is in phase with the current and the velocity over most of the acoustic range of frequencies is in phase with the force. Likewise the generated voltage is in phase with the velocity. Therefore the generated voltage and the current will be in phase and their ratio will be a pure resistance.

This is called motional resistance and is determined as follows. The force per unit current, or force factor, is

$$K = 1/10\,B\,l \quad \text{dynes per ampere} \qquad (\mathbf{13})$$

where $B$ = the flux density in gausses.

$l$ = the length of the moving conductor.

The generated back voltage per unit velocity is

$$E_g/v = B \text{ by } l \text{ by } 10^{-8}$$
$$= 10^{-7} \text{ by } K. \quad \text{volts per cm. per sec.} \qquad (\mathbf{14})$$

The velocity

$$v = \frac{F}{r} = \frac{K\,I}{r} \text{ cm. per sec.} \qquad (\mathbf{15})$$

The back voltage

$$E_g = 10^{-7}\,K\,v = \frac{10^{-7}\,K^2\,I}{r} \text{ volts} \qquad (\mathbf{16})$$

from which

$$R_m = \frac{E}{I} = \frac{10^{-7}\,K^2}{r} \text{ ohms} \qquad (\mathbf{17})$$

Having determined this motional impedance, the efficiency is obtained from the equation

$$N = \frac{R_m}{R_m + R} \tag{18}$$

In the case at hand, the length of the wire in the coil is 246 cm., and if the magnetic field has a density of 12,000 gausses

$$K = 1/10 \text{ by } 12{,}000 \text{ by } 246$$

$$= 0.295 \text{ by } 10^6 \text{ dynes per ampere}$$

$$R_m = \frac{10^{-7} K^2}{r} = \frac{10^{-7} \text{ by } (0.295 \text{ by } 10^6)^2}{3620} = 2.41 \text{ ohms}$$

The efficiency

$$N = \frac{2.41}{8 + 2.41} = 0.23$$

It might be expected that the efficiency in the general case will depend upon the flux density, the cut-off frequency, and the conductivity of the material used for the moving coil. An expression for efficiency in general terms will now be developed. Suppose that the coil form has negligible mass and that all the mass of the coil may be considered as useful conducting material. Let

$m$ = mass in grams.
$l$ = total length of conductor, cm.
$A$ = area of one conductor, cm.$^2$
$\delta$ = density, gms. per cm.$^3$
$\rho$ = resistivity, ohms per cm.$^3$
$B$ = flux density in gap, gausses.
$K$ = force factor, dynes per ampere in conductor.
$f_c$ = cut-off frequency.
$r$ = required damping, dynes per cm. per sec.
$v$ = velocity of vibration, cm. per sec.
$I$ = current in winding, amperes.

As before, the motional resistance

$$R_m = \frac{10^{-7} K^2}{r} \text{ ohms}$$

But $K = 1/10\, B\, l$

and $r = \pi f_c m = \pi f_c \delta A l$

Therefore $R_m = \dfrac{10^{-9} B^2 l}{\pi f_c \delta A}$

The resistance of the winding $R = \dfrac{\rho l}{A}$

The efficiency

$$N = \frac{R_m}{R + R_m} = \frac{\dfrac{10^{-9} B^2 l}{\pi f_c \delta A}}{\dfrac{\rho l}{A} + \dfrac{10^{-9} B^2 l}{\pi f_c \delta A}} = \frac{10^{-9} B^2}{\pi f_c \rho \delta + 10^{-9} B^2}$$

$$= \frac{1}{1 + 10^9 \dfrac{\pi f_c \rho \delta}{B^2}} \tag{19}$$

The efficiency is seen to be independent of the size of the unit, if the upper cut-off frequency, the flux density, and the mass conductivity of the coil are the same for all. High flux density and high mass conductivity (low $\rho\,\delta$) are needed. A field of 12,000 gausses is about as great as can be easily obtained. The value of $\rho\,\delta$ is smallest for aluminum being 7 by $10^{-6}$ as against 14 by $10^{-6}$ for copper. Curves of Fig. 4 show the efficiency of a 5000-cycle loudspeaker at different flux densities for both aluminum wire and copper wire coils. At 12,000 gausses the ultimate efficiencies are 57 and 40 per cent respectively.

In practical cases the coil form will not have a negligible mass; hence, a smaller amount of wire than mentioned above must be used. This is equivalent to an increase of $\rho\,\delta$ in equation (**19**) with a consequent reduction of $N$; efficiencies, however, up to 40 per cent for aluminum wire and 30 per cent for copper wire are attainable.

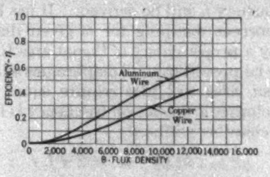

FIG. 4—ULTIMATE EFFICIENCY OF 5000-CYCLE LOUDSPEAKER FOR DIFFERENT DENSITIES

It is interesting to compare these efficiencies with that of the best hornless loudspeakers of today. A calculation shows the latter to be less than 5 per cent in the range of frequencies up to about 1000 cycles. The gain in efficiency by using the horn results in a great saving in amplifier capacity.

## IV. LOAD CAPACITY DETERMINATION

It might be expected that a loudspeaker of the type here described could be made to have a load capacity as great as desired by increasing its physical dimensions. If the unit is to respond to the high frequencies, however, there is a very definite limit to the size of the unit, and therefore to the power which it may radiate without overload. In all cases this maximum power is less for low frequencies because the maximum diaphragm velocity is smaller. This is due to the limited diaphragm displacement as determined by the clearance in the air cavity. Thus, the figure for maximum power must always be accompanied by a statement of the frequency at which this limit is reached. Since for a given maximum diaphragm displacement, the velocity is proportional to the frequency, and since the power radiated by the diaphragm is proportional to the square of the velocity, the maximum power output is proportional to the square of the frequency. Hence, if one watt is the load capacity of a given loudspeaker at 100 cycles, its capacity at 50 cycles will be only ¼ of a watt while at 200 cycles, it will be 4 watts. The above reasoning falls down in cases where mechanical weakness of the moving parts is the limiting factor.

Before dealing with load capacity in general terms, the maximum output of the particular design of loudspeaker previously given will be determined. Suppose that the maximum displacement of the diaphragm is arbitrarily fixed as that corresponding to a volumetric displacement of air equal to one-half the air chamber volume. In this case, this displacement will be 0.036 in. or 0.092 cms. The power output

$$W = \tfrac{1}{2} v^2 r \text{ by } 10^{-7} = \tfrac{1}{2} (2 \pi f x)^2 r \text{ by } 10^{-7}$$

$$= \tfrac{1}{2} (2 \pi f \text{ by } 0.092)^2 \times 3620 \text{ by } 10^{-7} = 0.605 \text{ by } 10^{-4} f^2$$

When $f$ is 100 cycles, $W$ is 0.605 watts.

A general expression for the maximum load capacity obtainable from a loudspeaker having a given upper cut-off frequency $f_c$ will be derived. It has been shown that the correct damping for a given diaphragm is obtained by a proper choice of throat area for the horn. It will now be proved that all diaphragms which require equal throat area will also require equal diaphragm chamber volumes if the cut-off frequency is fixed. The correct air chamber stiffness

$$s_2 = 2 \pi^2 \text{ by } f_c^2 m = 2 \pi f_c r \qquad (20)$$

Also

$$s_2 = \frac{1.4 A_d^2 \text{ by } 1.01 \text{ by } 10^6}{V_o} \qquad (21)$$

and

$$r = 41.2 \frac{A_d^2}{A_o} \qquad (22)$$

Substituting in equation (**20**)

$$\frac{1.4 A_d^2 \text{ by } 1.01 \text{ by } 10^6}{V_o} = \frac{2 \pi f_c \text{ by } 41.2 \text{ by } A_d^2}{A_o}$$

from which

$$V_o = \frac{5470}{f_c} A_o \qquad (23)$$

Thus, for a given cut-off frequency and a given throat area, the volume of the air cavity is constant.

The volumetric displacement of air in and out of the throat of the horn is definitely limited by this volume, and should preferably not exceed $\tfrac{1}{2} V_o$. The power is determined by the frequency, the volumetric displacement of air in and out of the orifice, and the orifice area in the following way;

$$W = \tfrac{1}{2} 41.2 A_o \left[ \frac{2 \pi f (\tfrac{1}{2} V_o)}{A_o} \right]^2 \times 10^{-7} \text{ watts}$$

Substituting for $V_o$

$$W = \tfrac{1}{2} 41.2 A_o \left[ \frac{\pi f \text{ by } 5470}{f_c} \right]^2 \text{ by } 10^{-7}$$

$$= 609 \left( \frac{f}{f_c} \right)^2 A_o \qquad (24)$$

From this it is seen that a large orifice is desirable to give large amounts of sound output. With available materials for the diaphragm, however, sufficient damping for obtaining a uniform response over the audio frequency range is secured only by the use of fairly small orifice areas. With an upper limit of $A_o$, therefore, there is a very definite upper limit of load capacity in a unit which responds uniformly up to $f_c$.

This upper limit of $A_o$ may be shown as follows: It has been stated previously that, with existing materials for the diaphragms, the thickness should not be less than a certain constant times its area.

$$t = 0.00035 A_d$$

The mass of an aluminum diaphragm for this assumption is

$$m = t A_d \text{ by } 2.7 = 0.00035 A_d^2 \text{ by } 2.7 \qquad (25)$$

The required damping

$$r = \pi f_c m = \pi f_c \text{ by } 0.00035 A_d^2 \times 2.7 \qquad (26)$$

But this value of $r$ is obtained by properly choosing $A_o$

$$r = \frac{41.2 A_d^2}{A_o} \qquad (27)$$

From equations (**26**) and (**27**)

$$A_o = \frac{41.2}{\pi f_c \text{ by } 0.00035 \text{ by } 2.7} = \frac{13900}{f_c} \qquad (28)$$

Taking $f_c = 5000$

$$A_o = 2.78 \text{ cm.}^2$$

It is seen that $A_o$ is definitely limited to this size no matter what diaphragm area may be chosen.

From equation (**24**), the maximum power for $f_c = 5000$ is definitely limited to

$$W = 0.68 \text{ by } 10^{-4} f^2 \qquad (29)$$

In view of the requirement of great power in the very low register for organ and drum reproduction, this limit is somewhat unfortunate. A knowledge of the limitation, however, prevents one from seeking in the dark for a single unit loudspeaker which will give larger outputs than the above at the low frequencies and still be responsive to the very high frequencies.

## V. METHODS OF OBTAINING HIGHER LOAD CAPACITY

There are two avenues of approach to the problem of obtaining greater load capacity. The first and most evident is to use a multiplicity of similar loudspeaker units as above designed, either on separate horns, or on a single horn having a divided or multiple orifice. By this means, the load could be divided equally between the several elements and thus prevent overloading of any one of them. A second and more practical approach problem is based on the following reasoning:

It was noticed that the load capacity of a loudspeaker which responds to 5000 cycles was greater at higher frequencies, and it is possible that such a single-element loudspeaker would handle without overload the upper register of music and speech for very large amounts of power. If a supplementary loudspeaker, (or a group of loudspeakers), could be made to take care of large volumes in the lower register, the different bands of frequencies could be divided properly between the two by means of a suitable electrical network, and thus, a great increase in load capacity could be effected. From the relations already given (equation (**24**)), it is seen that loudspeaker elements which do not have to respond to the higher frequencies can be made to have greater load capacity. Hence, by making sturdier units with heavier diaphragms and larger air chamber volumes, the necessary load capacity for the low-frequency range can be secured.

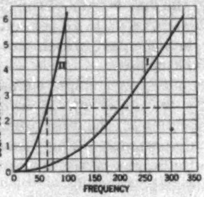

Fig. 5—Output Capacity

This is illustrated by the curves of Fig. 5, wherein curve 1 shows the load capacity of a small unit at different frequencies, this unit being capable of responding to 5000 cycles with uniformity; and curve 2 is for a loudspeaker with a lower cut-off frequency and, while similar in shape, it rises to higher values in the low frequency register. If the power level required is that corresponding to the dotted horizontal line, this low-frequency unit will be capable of supplementing the high-frequency unit down to a frequency corresponding to the dotted ordinate. The increase in power output capacity over what it would have been with higher-frequency unit alone is seen from a comparison of the powers where this vertical line cuts curves 1 and 2. In this case, the increase in power is about ten, whereas, if two similar small units had been used, the power output capacity would have only been doubled.

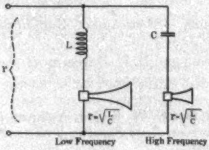

Fig. 6—Circuit Connection for Two-Element Loudspeaker

To make use of an arrangement of this kind, it is necessary to devise an electrical network which will divide the frequency bands properly between the two loudspeaker elements. Of the many circuits which might be employed, the circuit shown in Fig. 6 was chosen because (a) it has constant impedance over the band of frequencies for which the loudspeakers are purely resistive in their impedance, and (b) because for a given electrical input, the sum of the sound outputs of the two loudspeakers in the overlapping range is uniform. It is seen that the condenser in series with a small unit protects it from the damaging effect of large power at low frequencies, while the inductance in series with the low-frequency element prevents the higher frequencies from passing through this element which is incapable of responding to them.

'In the case of a demand for greater capacity than is possible with two loudspeakers of different size, a third and larger element may be added. A simple circuit for three is shown in Fig. 7. This is seen to be an extension of the circuit of Fig. 6 by the insertion of a capacity in series with the square, paralleled with a series combination of large unit and inductance. This circuit may also be made to have constant impedance over the band of acoustic frequencies and, by proper choice of the inductances and condensers, it may be made to divide the frequencies between the several elements so as to secure the maximum overall output capacity, as well as a uniform over-all response to a wide band of frequencies. Dr. J. Slepian of the Westinghouse Research Laboratories is responsible for the suggestion of this circuit.

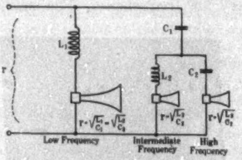
r
$L_1$
$C_1$
$L_2$
$C_2$
$r=\sqrt{\frac{L_1}{C_1}}=\sqrt{\frac{L_2}{C_2}}$
$r=\sqrt{\frac{L_2}{C_2}}$
$r=\sqrt{\frac{L_2}{C_2}}$
Low Frequency
Intermediate Frequency
High Frequency

Fig. 7—Circuit Connection for Three-Element Loudspeaker

It is evident that the use of two or more loudspeakers in this way is for an entirely different purpose from that of earlier attempts to secure a more uniform response to a wide band of frequencies by the use of several loudspeakers covering different ranges. In the present case, the small unit alone is capable of uniform response to a sufficiently wide band of acoustic frequencies for high-quality reproduction, but is found limited as to its output capacity for large power applications. The use of one or two supplementary loudspeakers with proper associated electrical network is made not to improve the quality of the reproduction, but to increase the output capacity. Each loudspeaker with its particular horn has a flat frequency response characteristic over a certain range, and in good designs, these ranges overlap considerably. The electrical network is what causes the tapering off of response of the individual loudspeakers in the overlapping range, so as to make the combined outputs uniform.

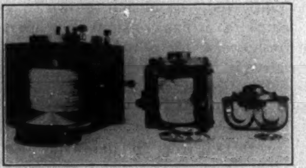
FIG. 8—THREE ELEMENTS FOR MULTIPLE LOUDSPEAKER

It is necessary, of course, to have a large horn on the low-frequency element in order to make it responsive down to very low frequencies. The smaller elements may be used in conjunction with smaller horns, however, since the electrical network allows very little low-frequency current to pass through them with the result that they do not have to radiate low-frequency sounds.

FIG. 9—THREE-ELEMENT LOUDSPEAKER

Fig. 8 shows the three elements of a loudspeaker of this type, with their corresponding moving elements placed in front of each. Fig. 9 shows the appearance of the loudspeaker mounted in cabinet form. This particular one responds from 60 to 5000 cycles with a load capacity of a 10-watt output at 60 cycles for the bass unit.

The details of design of such a combination of loudspeakers have been reserved for a later publication, but the foregoing will serve to illustrate in a general way the method of solving the problem of great load capacity.

## VI. SUMMARY

The methods of designing high-quality horn-type loudspeakers, having high efficiency and maximum load capacity, are shown. The limit of efficiency is determined by three factors: the cut-off frequency, the mass conductivity of the material used for the moving coil, and the flux density of the field in which the coil moves. Efficiencies up to 40 per cent are attainable in practise for loudspeakers which are uniformly responsive up to 5000 cycles.

The output capacity of a single element loudspeaker is determined by the upper cut-off frequency and the mechanical properties of the best known shapes and materials for diaphragms. This load capacity is proportional to the square of the frequency and at 100 cycles is approximately 0.6 watt.

A method of providing increased load capacity with greater simplicity than by using a great many similar units is to employ two or more loudspeakers covering different ranges of frequencies, but each having sufficient load capacity for its own range. With such an arrangement, fewer elements are required to give the desired increase in output capacity than if several small elements of similar design are employed.

The writer desires to thank Dr. J. Slepian for valuable suggestions, and Mr. W. O. Osbon for carrying through much of the design work and for his contributions to the development.

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## Discussion

**Harvey Fletcher:** There are some interesting and novel features connected with Mr. Hanna's paper, particularly the suggested use of three loud speakers for increasing the load capacity. His numerical calculations help to make clear the various factors affecting the efficiency of loud speakers.

It is well, however, to call attention to the fact that loud speakers are now being commercially used which have efficiencies greater than that described in his paper and which have practically a uniform response through a greater range of frequencies than indicated by the curves in his paper. The loud speaker used in connection with the public address system which is used in the Engineering Auditorium is such a one. A paper by E. C. Wente and A. L. Thuras entitled "A High-Efficiency Receiver for a Horn-Type Loud Speaker of Large Power Capacity" which appeared in the last issue of the *Bell System Technical Journal*, describes the design and construction of this type of loud speaker. The driving receiver is one of the moving-coil type and is connected to an exponential horn. The essential difference between this one and the one Mr. Hanna described is in the method of connecting the coil to the diaphragm and in the form of the air chamber connecting the diaphragm to the horn. In the design by Wente and Thuras the coil is connected directly to the diaphragm instead of by means of a spider. Also with the form of air chamber which they used, it is possible to use a larger diaphragm without sacrificing efficiency at the high frequencies, thus making it possible to radiate more energy at the low frequencies. In this paper Wente and Thuras also describe three methods of making the measurement of the absolute efficiency of the receiver, (1) by calculation based upon a theory similar to that given in Mr. Hanna's paper, (2) by experimental measurements of the motional impedance of the receiver, and (3) by measuring the acoustic pressure and the mechanical impedance near the diaphragm. The close agreement between the three methods shows the reliability of the measurements. It seems to me that it would be desirable if some measurements of this sort were made upon the type of receiver described by Mr. Hanna.

The type of loud speaker having such a high efficiency is in commercial use in connection with the Vitaphone and Movietone types of talking motion pictures. As commercially produced in quantities numbering several thousand, an average efficiency of the order of 30 per cent has been realized.

I should like to ask Mr. Hanna how the response curve shown in Fig. 3 of this paper was obtained and also what the zero line represented, and what sort of argument he used for deducing Eq. **6**. In the Vitaphone loud speaker which was described by Wente and Thuras a diaphragm of about one-half the thickness as called for by this formula was used and it has been found to be free from any such resonance as described in his paper.

**A. E. Kennelly:** The paper relates to conditions in an electric circuit and an associated "acoustic circuit." While it is not strictly accurate to speak of "acoustic circuit," yet there are so many points of resemblance between an acoustic system and an associated electric system, that the inaccuracy may be overlooked for the sake of the convenience. The power input of the acoustic system is on the electric side $I^2R$, and on the acoustic side $v^2\,r$, where $v$ is the velocity and $r$ the acoustic resistance, both in appropriate units. Equating the two,

$$I^2R = v^2\,r \quad . \quad . \quad . \quad . \quad . \quad \text{(power units)}$$

It is necessary to employ the same unit of power for both sides. It seems that, at the present time, the c. g. s. electro-magnetic system, the parent of our practical, volt-ampere-ohm system, is the most convenient in which to select the unit of power on both sides of the equation. In that case, $I$ will come out in abamperes, $R$ in abohms, $v$ in cm. per sec., or kines, and $r$ in acoustic abohms. Every one knows what these units mean, and they do not have to be learned afresh. If we do not use the c. g. s. system, we have to "create new unit" names, in order to complete the equation. The mechanical or "acoustic ohm" is not the same as the mechanical or "acoustic abohm," because it belongs to the practical system, and has one of several possible different magnitudes.

I think we are much indebted to the author for giving us a paper in which the quantities involved are expressed in simple arithmetical equations, which can be readily understood, if the proper units are employed.

**W. C. Jones:** There are two or three points to which I should like to call attention.

The first of these has to do with load capacity. After making certain assumptions relative to the mechanical properties of available diaphragms and the permissible volumetric displacement in the cavity which forms the coupling stiffness between the diaphragm and the horn load, the author concludes that the output from a single loud speaker is limited to approximately 0.6 watt, if it is to respond well at high frequencies. The so-called lumped-constant system has therefore been abandoned in favor of a system in which the various masses instead of being rigidly coupled are joined by members of moderate stiffness. In this connection it is of interest to note that the experience gained in connection with the production of talking motion pictures, has shown that a single loud speaker of the lumped-constant electrodynamic type can be operated at output levels three to four times higher than the limiting level set by this paper without serious distortion or sacrifice in high-frequency response. The limiting factors appear to be heating and mechanical strength of the moving parts rather than distortion due to air space phenomena.

I should like to ask in connection with Fig. 3 whether the efficiency based on motional impedance measurements and computed in accordance with equation **18** is substantially uniform from 150 cycles to 4000 cycles. It is my impression that, if the acoustic output from the motor element to the throat of the horn bears the same relation to the electrical input at all frequencies, the response curve measured at a point in front of the loud speaker will not be flat but will rise at the higher frequencies.

One other point is the matter of field density. All who have worked with electrodynamic structures appreciate the importance of securing high flux densities in the air-gap, and will, I believe, agree with Mr. Hanna that an air-gap density of 12,000 is about as high as is obtained commercially in circuits involving a good grade of magnetic iron. In this connection it is of interest to note that certain of the cobalt alloys have higher saturation densities than magnetic iron, and make possible air-gap densities of the order of 20,000 without excessive dissipation of power in the field winding.

**C. R. Hanna:** The paper by Messrs. Wente and Thuras, mentioned by Mr. Fletcher in his discussion, was published subsequent to the time my paper was submitted to the Institute. This paper describes the design of loud speakers which correspond most nearly to the smallest of the three elements described in my paper because the response is uniform up to about 5000 cycles. Since only one type of loud speaker is described, I judge that the method of obtaining sufficient load capacity for auditorium use is to employ a great many of these units coupled to a single horn with a divided orifice or to as many horns. It is interesting to note that in the lower range of frequencies, say around 60 cycles, at least 10 to 15 of these units would be required to provide the same load capacity as is obtained by the use of three dissimilar units as described in my paper.

Mr. Fletcher asks for the reason underlying Eq. **6**, in which the thickness of the diaphragm is equal to or greater than a certain constant times the area of the diaphragm. The constant in this equation was determined from experience as one which would ensure piston action of the diaphragm up to 5000 cycles, as well as adequate mechanical strength. Mr. Fletcher states further that the diaphragm as described by Wente and Thuras is approximately half as thick as would be required by the relation given in Eq. **6** and is found to be free from resonance within the acoustic range of frequencies. I note, however, from the curves of the paper by Wente and Thuras, that some resonance does occur in the range of frequencies from 3000 to 5000, and it is my belief that this resonance is caused by breaking up of the diaphragm.

In answer to the question regarding the method of taking the response curve which was given in the paper, this was done in the usual way by measurement of radiation pressure with the condenser transmitter at different frequencies in a damped room. The zero line in the graph is arbitrarily chosen.

Dr. Kennelly urges the adoption of a more convenient nomenclature for mechanical and acoustical impedance. There is no doubt that standardization along this line will come about as the number of workers in this special branch of engineering increases.

Mr. Jones asks if the spring method of mounting the driving coil upon the diaphragm was used to give greater load capacity than is possible with the unit structure. This is one of the reasons, the greater load capacity resulting from the greater air cavity possible with the divided structure. He points out that it has been his experience that heating of the moving coil limits the output of loud speakers more than air-cavity clearances. Our experience has been that if the full range of frequencies in music and speech is applied to the loud speaker, limitation in output will occur in the low-frequency range because of cavity clearances. Of course if the low frequencies are not applied to the loud speaker in their correct relative proportion, it is quite possible that greater amounts of power may be applied to the loud speaker or speakers, in which case the coil may become overheated.

Another advantage of the compliance method of mounting the coil upon the diaphragm is that for a given field density the efficiency will be higher than in the unit structure. In the paper by Wente and Thuras, efficiencies of the order of 50 per cent are obtainable only by the use of fields as strong as 20,000 gausses. If such fields were used in the divided structure of coil and diaphragm assembly, efficiencies of the order of 75 per cent would be obtainable for aluminum coils and 60 per cent for copper coils. These figures are based on a weight factor of 90 per cent.

In the loud speakers described in my paper, no attempt has been made to go the limit in obtaining these high efficiencies. With copper-wire coils and field densities of the order of 12,000 the efficiency for the high-frequency units will be of the order of 25 to 30 per cent, which is of the same order as the commercial efficiencies obtained in loud speakers described by Wente and Thuras.

The field density required to obtain equal efficiency in the lower-frequency elements is less than the above because a greater mass of conductor may be used in the moving member. In the bass unit, for example, the field strength is about 5000 gausses, and the coil which drives the diaphragm has a mass of nearly ½ lb.

# Certain Topics in Telegraph Transmission Theory

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***Synopsis.***—*The most obvious method for determining the distortion of telegraph signals is to calculate the transients of the telegraph system. This method has been treated by various writers, and solutions are available for telegraph lines with simple terminal conditions. It is well known that the extension of the same methods to more complicated terminal conditions, which represent the usual terminal apparatus, leads to great difficulties.*

*The present paper attacks the same problem from the alternative standpoint of the steady-state characteristics of the system. This method has the advantage over the method of transients that the complication of the circuit which results from the use of terminal apparatus does not complicate the calculations materially. This method of treatment necessitates expressing the criteria of distortionless transmission in terms of the steady-state characteristics. Accordingly, a considerable portion of the paper describes and illustrates a method for making this translation.*

*A discussion is given of the minimum frequency range required for transmission at a given speed of signaling. In the case of carrier telegraphy, this discussion includes a comparison of single-sideband and double-sideband transmission. A number of incidental topics is also discussed.*

* * * * *

## SCOPE

THE purpose of this paper is to set forth the results of theoretical studies of telegraph systems which have been made from time to time. These results are naturally disconnected and in order to make a connected story it has been necessary to include a certain amount of material which is already well known to telegraph engineers. The following topics are discussed:

1. The required frequency band is directly proportional to the signaling speed.

2. A repeated telegraph signal (of any length) may be considered as being made up of sinusoidal components. When the amplitude and phase, or real and imaginary parts, of these components are plotted as ordinates with their frequencies as abscissas, and when the frequency axis is divided into parts each being a frequency band of width numerically equal to the speed of signaling, it is found that the information conveyed in any band is substantially identical with that conveyed in any other; and the bands may be said to be mutually redundant.

3. The minimum band width required for unambiguous interpretation is substantially equal, numerically, to the speed of signaling and is substantially independent of the number of current values employed.

4. A criterion of perfect transmission is selected; and a discussion is given of the characteristics which the received wave must have to be non-distorting with the requirement that the frequency range should not be greater than necessary.

5. Directions are sketched for specifying systems to meet this requirement.

6. Several alternative criteria of distortionless transmission are considered and a method for computing the corresponding transmission characteristics of the circuit is explained and illustrated.

7. An analysis is given of the carrier wave, and it is shown that the usual carrier telegraph requires twice as much frequency range as the corresponding d-c. telegraph, other things being equal.

8. A discussion is given of two alternative methods for overcoming this inefficiency of carrier telegraphy, namely, the use of phase discrimination and of a single sideband.

9. After the d-c. and carrier waves have thus been analyzed a corresponding analysis is given of an arbitrary wave shape, including these two as special cases. Calculations are given on the shaping of the transmitted wave so as to make the received wave perfect.

10. A discussion is given of the dual aspect of the telegraph wave. The wave may be looked on either as a function of $\omega$, requiring the so-called steady-state method of treatment, or as a function of $t$ requiring the so-called method of transients. It is shown that the steady-state theory can be made to yield the information necessary to specify the characteristics of an ideal system.

11. A discussion is given of the effect of interference and departures from ideal conditions.

The economy in frequency range, indicated under 2 and 3, should be considered as a theoretical limit which cannot be attained in practise but which can be approached, the closeness of approach depending on the degree with which the requisite conditions are fulfilled. In practise, it is essential to limit the cost of terminal apparatus and this, in turn, may lead to imperfect utilization of the frequency range.

In certain portions of the paper the discussion is limited to ideal telegraph systems and it is the characteristics of such systems which are referred to above (4, 5, and 6). These ideal systems have certain ideal transmission characteristics; while the reader is given sufficient information to specify suitable equilizers to produce an ideal system, there is no information given as to how to proceed to build equalizers to meet the requirements. It is not within the scope of the paper to enter into the practical questions of cost and detailed construction of signal shaping devices. While these subjects are of great importance, it is thought best to confine the paper to theory. Lest the reader should think this lack of equalizer theory a fatal weakness in the whole theory presented, attention is called to the discussion of generalized wave shape; where directions are given for approaching the ideal case as closely as desired, by shaping the sent wave to take care of any residual imperfections in the transmission characteristic. Finally, under the discussion of interference, mention is made of the effect of departures from the ideal in the matter of signaling speed, transmission characteristic, etc.

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### SYMBOLS

| | |
|---|---|
| $A(t)$ | Indicial admittance. |
| $A_n$, $A$ | The coefficient of the $n$th cosine term in a Fourier series. |
| $a_h$, $a$ | Magnitude factor of the $h$th signal element. |
| $a$ | General quantity in formulas. |
| $B_n$, $B$ | The coefficient of the $n$th sine term in a Fourier series. |
| $b_h$, $b$ | Magnitude of the $h$th step of a rectangular stepped signal element. |
| $b$ | General quantity in formulas. |
| $b$, $b_0$, $b_1$, $b_2$ | Susceptance (coefficient of imaginary part of transfer admittance). |
| $C_n$ | Real part of discrimination factor. |
| $C'_n$, $C''_n$ | Defined in Appendix IV. |
| $\gamma$ | Numerical factor near unity. |
| $\delta$ | An arbitrary increment of frequency. |
| $E(t)$ | Wave (usually voltage wave) as a function of $t$. |
| $e$ | Base of natural logarithm. |
| $F(\omega)$, $F$ | Shape factor. |
| $F'(\omega)$, $F''(\omega)$ | Defined in Appendix IV. |
| $F_0$ $F_\Delta$ | Specific shape factors. |
| $f(t)$ | Wave form. |
| $g$, $g_0$, $g_1$, $g_2$ | Conductance (real part of transfer admittance). |
| $g(t)$ | Envelope of a carrier wave. |
| $h$ | Any positive integer, indicates order of signal element. |
| $H(\omega)$ | An abbreviation for $\frac{\sin \omega/4s}{\omega} Y(\omega) e^{-i\omega}$ |
| $\theta$ | Phase angle of carrier wave. |
| $I(t)$, $I$ | Wave as a function of $t$. |
| $I_h$ | Wave due to $h$th signal element. |
| $i$ | Unit of imaginary quantity, $i^2 = -1$. |
| $k$ | An integer or zero. |
| $\lambda$ | Variable under integration sign. |
| $m$ | An integer or zero. |
| $N$ | Number of signal elements in one repetition of a signal. |
| $n$ | Any integer or zero, indicates order of sinusoidal component. |
| $p$ | $2\pi$ times frequency of repetition of a signal. |
| $q$ | An integer or zero. |
| $R$ | A constant. |
| $r$ | A subscript referring to receiving end. |
| $S_n$, $S$ | The coefficient of the imaginary part of the discrimination factor. |
| $S'_n$, $S''_n$ | Defined in Appendix IV. |
| $s$ | Speed of signaling. |
| $s$ | A subscript referring to sending end. |
| $T$ | Duration of one signal repetition. |
| $t$, $t'$ | Time. |
| $\tau$ | An arbitrary interval of time. |
| $Y(\omega)$, $Y$, $Y_0$ | Transfer admittance. |
| $Y_1$ and $Y_2$ | Components of $Y$. |
| $\overline{Y}$ | The conjugate of $Y$. |
| $\phi$ | Phase shift of a given circuit. |
| $\omega$ | When positive, equals $+2\pi$ times the frequency; when negative equals $-2\pi$ times the frequency. |
| $\omega_c$ | $2\pi$ times carrier frequency. |

### PRELIMINARY DISCUSSION

A simple telegraph system is obtained by connecting a telegraph key and battery in series with a line at one end, the other end of the line being connected to a sounder, both ends of the system being grounded. Signals are transmitted by opening and closing the key, which causes corresponding movements of the sounder at the receiving end if the system is properly designed and adjusted. Suppose it is desired to transmit the Morse letter *a* over the system. This may be done by closing the key during one unit of time, opening it for one unit of time, closing it for three units of time and finally opening it for a sufficient period to assure the receiving operator that the signal is completed. This simple telegraph system illustrates two characteristics of telegraph communication as the term is here used which will serve, for the purposes of the present paper, to distinguish telegraphy from other forms of electrical communication. These characteristics are:

1. The time is divided into approximately equal units which will be called time units.
2. There is a finite number of conditions, and each time unit is characterized by a single one of these conditions.

In the simple illustration given, where the first time unit is characterized by closing, the result is the "dot" of the letter *a*. The second time unit is characterized by opening the key. Thus, the total number of conditions is two, open and close. This is in sharp distinction to the case of telephony where there are neither simple numerical relations between the various time intervals, nor a finite number of possible current values.

In this simple illustration the rate with which the new condition establishes itself throughout the system is not generally the same on opening and closing. This is because there is a change in the terminal impedance as well as in the voltage applied. The system would be simpler, mathematically, if the keys were arranged to substitute for the battery an impedance equal to that of the battery. It will be assumed in this paper that the impedance is not altered when one condition is substituted for another. This is substantially true for polar telegraphy but not for single-line telegraphy.

In the system under discussion there are two conditions, battery and no battery. In the usual forms of polar telegraphy, there are also two conditions, corresponding to positive and negative battery potentials impressed at the sending end. In well-known forms of submarine telegraphy there are three conditions corresponding to positive battery, negative battery, and ground or zero voltage. Throughout the paper, unless otherwise stated, the discussion will apply to any number of conditions and will, therefore, include the cases enumerated as special cases.

Due to the distorting effect of the telegraph circuit the part of the total signaling wave which is originally associated with a given time unit does not remain confined to one time unit throughout. There is overlapping between the wave portions originating in successive time units. It is, of course, important to follow the history of a given contribution to the signal wave regardless of whether it is prolonged to occupy more time than it did originally. To this end the term *signal element* is introduced and is defined as the contribution to the signal ascribed to a given time unit. Whereas a time unit is of a definite duration uniquely determined by the speed of signaling, the signal element ascribed to a specific time unit may, by the use of signal shaping, be made to extend into adjacent time units.

The concept which has been discussed under the term "conditions" is an important one and it is desirable to formulate it more precisely. It will be assumed, when not otherwise stated, that the shapes of the successive signal elements are the same, so that they differ only by a factor which may differ from element to element. For illustration: in the case of the submarine cable system the wave shape of the impressed voltage is the same in all three conditions, being rectangular, and there are three proportionality factors $+a$, 0, and $-a$. In the general case any signal element may be expressed by the product

$$a_h f(t)$$

where $a_h$ is a real factor which may vary from one signal element to another and where $f(t)$ is a function of time. The origin of $t$ is, of course, a fixed instant with respect to the signal element. The function $f(t)$ will be called the *wave form*. It is determined by the wave form at the sending end, and by the transmission characteristics of the system between the sending end and the point under consideration. It is not affected by the particular signal or form of intelligence being transmitted over the system. The factor $a_h$ will be called the *magnitude factor*. It differs from one signal element to another but is the same in all parts of the system and, in fact, in all systems transmitting the same signals.

*Speed of signaling*, $s$, is usually specified in dots per second and is defined as the number of signal elements per second divided by two.

*D-c. telegraph* is characterized by a rectangular signal element; the voltage is held constant during the whole time unit.

A telegraph circuit may be considered as a network upon which a signaling wave is impressed at one point, called the sending end, and from which a signaling wave is derived at another point, called the receiving end. In the illustrations given, the sent waves were voltage waves. This is not necessarily the case in order for the discussion to apply. The sent wave may be a current wave, or it need not even be electrical. By providing suitable coupling the sent wave may be mechanical or, say, in the form of variations in a light beam. All that is required is that the system should be linear, including the coupling between mechanical and electrical circuit elements. Similarly with the receiving end it is permissible to consider either the voltage across the receiving device, the current through it, or the motion of the receiving device to be the received wave; provided the device is linear. An important exclusion is the ordinary telegraph relay which is equipped with stops and which, therefore, is a non-linear device. The siphon recorder on the other hand is probably substantially linear. The theory of mechanical impedances and of coupling between mechanical and electrical impedance elements will not be dealt with in this paper.

## PROPORTIONALITY BETWEEN SPEED OF SIGNALING AND TRANSMITTED FREQUENCY BAND

It will aid the discussion to assume that the signal considered is repeated indefinitely at equal intervals. While this is convenient, it constitutes no real limitation on the generality of the analysis, because the intervals of repetition may be made as large as desirable. There is nothing to prevent us from making the interval very great, say, an hour or a year.

Take first the case of any arbitrary signal made up of any number of elements and any finite number of different magnitude factors (current values) and repeated an indefinitely great number of times. Such a periodic wave can be resolved into direct current and a series of sinusoidal components. The lowest frequency component has a period equal to the period of repetition of the signal. The next component is of double the frequency or one-half the period of the first. The third component is of triple frequency or one-third period, and so forth. Certain components may, of course, be of zero amplitude, *i. e.*, entirely lacking. While there always is a definite lowest frequency component, there is generally no highest component; in other words, the total number of components is usually infinite.

The transmission medium may alter the magnitude and phase of the sinusoidal components. Some of them may be substantially completely suppressed. Further, the medium may introduce components either because it is non-linear or because interfering waves exist. The net result is a deformation of the original wave.

Now consider another signal which is just like the one discussed except for the distinction that the signal elements of the sent wave are of half the duration, that is to say, everything happens twice as fast and the signals are repeated twice as frequently. It will be obvious that the analysis into sinusoidal terms corresponds, term for term, with the case just considered, the difference being that corresponding terms are of exactly twice the frequency. Now if the second telegraph system transmits currents up to twice the frequency of the first and if, further, the transmitted currents are treated the same in respect to attenuation, phase shift, interference, and other modifying factors as the corresponding currents in the first system (*i. e.*, currents of half the frequency), then the received wave in the second case will be the exact counterpart of the wave in the first case; that is, its deformation will be the same. Generalizing, it may be concluded that for any given deformation of the received signal the transmitted frequency range must be increased in direct proportion to the signaling speed, and the effect of the system at any corresponding frequencies must be the same. The conclusion is that the frequency band is directly proportional to the speed.

It is apparent on examination of existing telegraph systems that the factor relating band width and line speed does, in fact, vary from system to system. The reason for this is that different systems utilize the available range with different effectiveness. In the first place, the various components suffer different attenuation and phase changes from system to system. Secondly, interference varies from system to system; and there are also secondary imperfections. The question then arises: What is the limiting value for this factor under ideal condtions? It is one of the purposes of the following analysis to answer this question.

## ANALYSIS OF D-C. WAVE

Initially we shall assume a system which is ideal in all respects of interest. Later on we shall indicate how these ideal conditions can be approximated and what will be the effect of small departures from the ideal conditions.

Let us consider again an arbitrary signal repeated at regular intervals. As has been brought out above, such a signal has an infinite number of components and can be represented by a Fourier series. Suppose that each component is measured at the receiving end, and suppose that proper allowance is made for the known effect of the circuit on each component, it is then possible to construct each component as it was impressed on the sending end. If all the components were received and measured, it would be possible to reconstruct the original wave without deformation. Now for a given wave form, (which in this case is rectangular) the magnitude and phase-angle of the individual sinusoidal components of the impressed wave are determined by the values of the quantities $a_h$ of the signal elements, and equations can be set for computing each component. Conversely these equations can be solved if a sufficient number of them is taken so that the $a$'s are completely determined. Now the number of $a$'s is finite, whereas the number of sinusoidal components is infinite. It follows from simple equation theory that all of the equations cannot be independent; and, in fact, since each component (with rare exceptions)[2] yields two constants, it follows that a number of components approximately equal to one-half the number of signal elements should be sufficient to determine the $a$'s completely, provided the components are chosen to be mutually independent. It is concluded that full knowledge of $N/2$ sinusoidal components is necessary to determine the wave completely. It will be shown below that this number is also sufficient.

The mathematical work of analyzing the wave into its sinusoidal components is carried through in Appendix I. It is there shown that if the magnitude factors of $N$ successive signal elements are given the values $a_1$, $a_2$, $a_3$, etc., up to $a_N$, and if the signal is then repeated,[3] the expression for the applied voltage can be written in the following form:

$$E\,(t) = A_0/2 + A_1 \cos pt + A_2 \cos 2\,pt + \text{etc.}$$
$$+ B_1 \sin pt + B_2 \sin 2\,pt + \text{etc.}$$

where $p/2\,\pi$ is the frequency with which the signal is repeated and where the $A$'s and $B$'s can be computed from the formula

$$(A_n - i\,B_n) = F\,(\omega)\,(C_n - i\,S_n)$$

in which $$F\,(\omega) = \frac{8 \sin \omega/4\,s}{\omega/s}$$

$$C_n = (1/N)\,(a_1 \cos n\,\pi/N + a_2 \cos 3\,n\,\pi/N + \ldots + a_N \cos (2\,N - 1)\,n\,\pi/N)$$

$$S_n = (1/N)\,(a_1 \sin n\,\pi/N + a_2 \sin 3\,n\,\pi/N + \ldots + a_N \sin (2\,N - 1)\,n\,\pi/N)$$

$s$ is the speed of signaling, and

$\omega$ is $2\,\pi$ times the frequency of the component.

$F\,(\omega)$ is independent of the values of the $a$'s and depends only on $n$ and the wave form within one signal element, which in the present case is rectangular. Its value is altered if, for instance, curbed signals are used. It may, for convenience, be called the *shape factor*. It should be emphasized that $F\,(\omega)$ is independent of the intelligence transmitted. $C_n - i\,S_n$ on the other hand is independent of the type of wave employed, but depends only on the particular signal which is considered. $C_n - i\,S_n$ is thus determined by the particular intelligence being transmitted and, in turn, determines that intelligence completely. This factor may be called the *discrimination factor*. An examination of the expressions for $C_n$ and $S_n$ discloses the dependence predicted above and will enable us to select components which are independent. Both $C_n$ and $S_n$ are made up of periodic terms, namely, cosines and sines. If the value of $n$ is increased by the value $2N$ each one of these periodic functions has its argument increased by an integral multiple of $2\pi$ and is, therefore, unaltered. Similarly if $n$ is increased by $N$ the arguments are increased by an odd multiple of $\pi$ and all the terms are simply changed in sign. Further, if the expressions for $C_n$ and $S_n$ are written down for the values $N - n$, and if it is remembered that $\cos(\pi - x) = -\cos x$ and $\sin(\pi - x) = +\sin x$, it will be found that

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[2] $B_0$ and $A_{N/2}$ are identically zero.

[3] A convenient but not a necessary restriction.

$$C_{N-n} = -C_n \text{ and } S_{N-n} = S_n$$

The results may be written

$$C_{N+n} = -C_n,\ S_{N+n} = -S_n$$

$$C_{2N+n} = C_n, \text{ and } S_{2N+n} = S_n$$

Successive applications of the last formula give

$$C_{2kN+n} = C_n, \text{ and } S_{2kN+n} = S_n$$

where $k$ is any integer.

These relations are illustrated in Fig. 1, in which the discrimination factor is plotted as a function of $n$. The signal which is illustrated in this figure may be referred to as the $c$ signal. It is made of 10 signal elements whose successive magnitude factors are 1, 0, 1, 0, 0, 1, 0, 0, 0, 0. An inspection of the figure will show the symmetrical relation between points in adjacent bands of width $N/2$, or 5 in this specific example. Suppose that the $c$ signal is sent in $T$ seconds. Then the frequency corresponding to the fifth harmonic is $5/T$ (generally $N/2T$) which is also the speed of signaling.

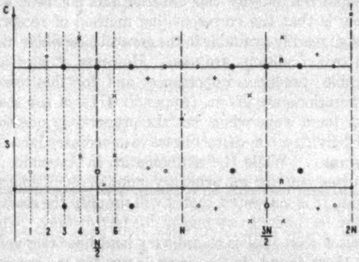

FIG. 1—DISCRIMINATION FACTOR OF $C$ SIGNAL

**Showing the symmetry and redundancy of successive bands. The corresponding points in the various bands are indicated by the same symbol**

If $C_n$ and $S_n$ have been determined throughout any one of the bands, their values (and, $F(\omega)$ being known, also the values of $A_n$ and $B_n$) are immediately known for the whole range from zero to infinity. Each such band contains all the information about the signal that the totality of bands from zero to infinity contains. One such band (or its equivalent) is necessary and sufficient to determine the original signal. It will be understood that information about $F(\omega)$ is not intelligence in the sense here considered. It is not necessary that the receiving end should have any information about $F(\omega)$ at the sending end and consequently, no frequency range or line time need be set aside for transmitting such information. The frequency range which must be transmitted to specify one band is numerically equal to the speed of signaling.

A special case occurs if the transmitted band is chosen such that the shape factor is zero at some point within it. Then $A_n$ and $B_n$ corresponding to this term, will be zero and the values of $C_n$ and $S_n$ are indeterminate. The mathematical treatment of this case would be long and difficult and it is, moreover, thought that these cases are of little practical interest. For these reasons no further discussion will be given to them.

### DISTORTIONLESS TRANSMISSION

It is obvious that with a finite transmitted frequency range and with a rectangular sent wave, there will be deformation of the wave form. It is, however, possible to have a deformed wave and have a receiving device such that a perfect signal is received. Suppose, for instance, that the receiving device records the value of the wave at the mid-instant of the time unit corresponding to each signal element. Then all that matters is the value of the wave at that instant; it does not matter how much it is deformed in intervening intervals. For convenience the term *non-distorting wave*, will be introduced and will be defined as a wave which produces perfect signals. A non-distorting wave may or may not be deformed. The criterion for a non-distorting wave will vary with the manner of receiving the signal. In this paper, when not otherwise stated, the illustration just indicated will be taken as the criterion, *i. e.*, a wave will be said to be non-distorting when the value at the mid-instant of any time unit is proportional to the magnitude factor for the corresponding element. In Appendix II-A, the shape factor for this kind of wave is computed. When the transmission characteristic of the system is such that the received wave has this shape factor, the received wave is non-distorting regardless of the number of distinct magnitude factors employed. It will be understood that this criterion is illustrative only. Later, alternative criteria will be illustrated and discussed sufficiently to enable the reader to construct his own criterion proper for the system in which he is interested.

Before proceeding to determine the characteristics of the telegraph system which insure the ideal shape factor just discussed it is worth while to broaden the subject somewhat by considering what other shape factors are capable of producing the same results. Appendix II-A gives the deduction of more general shape factors which meet the requirements of being ideal. In Fig. 2, *a* is a diagram of the shape factor deduced as ideal, above. It is shown in Appendix II-A that shape factors symmetrical about $2\pi s$, after the manner illustrated at *b* in Fig. 2, do not contribute anything to the current value at the middle of the signal elements. Hence it is deduced that shape factors such as shown at *c* are also ideal in the same sense. There are obviously an infinite number of these shape factors. In addition, there are an infinite number of purely imaginary shape factors having the type of symmetry about $2\pi s$ which do not contribute to the value of the wave at the middle of the signal element. Each one of this infinity of imaginary shape factors may, of course, be combined with any one of the infinity of real shape factors spoken of above.

In order to visualize better the theoretical results obtained so far, these results will be stated in terms of the design of a telegraph circuit. What must be the characteristics of a telegraph circuit in order that the application of the rectangular voltage wave whose shape factor is $F_s$ shall result in the non-distorting received wave just discussed, whose shape factor may be taken as $F_r$? One answer is that the transfer admittance[4] of the circuit $Y$ should be made such that $F_r = Y F_s$. It will be understood that the quantities $Y$ and $F_r$ may be complex. If the condition just stated were met, transmission would be instantaneous. This imposes an unnecessary restriction on the transfer admittance $Y$. The signal will still be distortionless if all the components suffer a constant lag $\tau$. If all the components are given a phase lag, which, when specified in angular measure, is directly proportional to the frequency, the received wave is not changed in shape but merely displaced in time and this is, of course, permissible. This leads to the following expression:

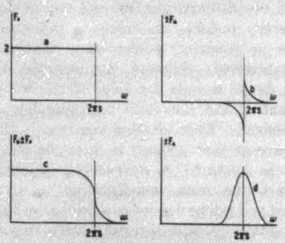

FIG. 2—IDEAL SHAPE FACTORS

Here the criterion for distortionless transmission is that the height of the middle of each signal element should be undistorted

*a* and *c* represent real shape factors which produce a non-distorting wave,—*b* and *d* shape factors which may be added without producing distortion, the former representing a real and the latter an imaginary value

$$Y = \frac{F_r}{F_s}(\cos\omega\tau - i\sin\omega\tau)$$

for the transfer admittance where $\tau$ is the delay. Once the desired value of $Y$ has been found by this method, the problem is reduced to measuring the phase and attenuation characteristics of the circuit and designing suitable attenuation and phase correctors to make the total transfer admittance equal to $Y$. The actual design of attenuation and phase correctors does not come within the scope of the present paper.

Appendix II-B has been added for the purpose of making a concrete application. It may be omitted without loss of continuity in the theory.

The criterion of perfect transmission in what precedes has been that the current value at the midpoint of the time unit should bear a constant ratio to the impressed voltage. It will be noted that this is considerably different from the case of ordinary two-condition telegraphy, where the criterion for perfect transmission is that the interval between the instants when the current passes through the mean value (or some other specific value) shall be the same as the corresponding interval at the transmitting end. The principal reason why this criterion has not been used above, is that the corresponding method of reception is not so readily available in the general case where more than two conditions are used. However, it is of considerable practical importance and for this reason, computations are given, (Appendix III), of the shape factor for a wave which has the property in question, *i.e.*, of giving a non-distorting wave in ordinary land-line telegraphy. While the mathematics in Appendix III is carried out for an arbitrary number of magnitude factors, it is suggested that it will simplify the reader's picture to think of two magnitude factors only. Then the discussion applies to ordinary land-line telegraphy. It is there found that a shape factor for the received wave which satisfies this condition is

$$F_r = 2\cos\omega/4s, \text{ when } 0 < \omega < 2\pi s$$
$$F_r = 0, \text{ when } 2\pi s < \omega$$

For d-c. telegraphy (rectangular sent wave) this corresponds to a transmission characteristic given by the equation

$$Y = \frac{F_r}{F_s}(\cos\omega\tau' - i\sin\omega\tau')$$

$$= \frac{\omega}{4s}\cot\frac{\omega}{4s}(\cos\omega\tau' - i\sin\omega\tau'), \quad \text{when } 0 < \omega < 2\pi s$$

$$\text{and } Y = 0, \quad \text{when } \omega \geq 2\pi s$$

This particular shape factor has the disadvantage that the amplitude is a function of the signal combination; in particular, a long continuation of reversals finally approaches zero in amplitude. To overcome this, it is possible to add shape factors which are symmetrical about the signaling frequency, such as are shown in Fig. 3, and discussed more fully in Appendix III.

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[4] The term admittance and the notation $Y$ is used to denote the ratio of the numerical value of two waves regardless of their nature. This is a convenient generalization of the customary usage, where this terminology is confined to the case where the numerator of the ratio is a current, and the denominator a voltage.

By way of further illustrating the method, the shape factor is worked out for a received wave having the property that the *area* under the wave for a time unit is proportional to the current at the transmitting end. This case may be of interest in some methods of picture transmission where the integrated exposure over a small interval of time may be important. Other criteria for distortionless transmission suggest themselves. For example, the signal may be taken distortionless when the area under the wave for the center fifth of the time unit is proportional to the sent current. Such cases may be of interest in certain types of printer reception where the current flowing during the center fifth of each element might be the quantity which is of interest. As another example, it may be that the slope of the received current as well as the current value determines the operation of the receiving device, in which case some such function as $a\,I + b\,\dfrac{d\,I}{d\,t}$ would probably be a suitable quantity in terms of which to define distortionless transmission. It is thought that the reader who is interested in any specific receiving device will have no difficulty either in formulating a suitable criterion or in computing the corresponding shape factor in accordance with the method illustrated. In the meantime, the current at the center of the signal element will be taken as the criterion.

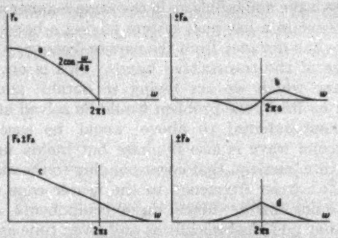

Fig. 3—Ideal Shape Factors

In this figure, the criterion of distortionless transmission is that the width or duration of each signal element at the mean-value point should be uddistorted

*a* and *c* represent real shape factors which produce a non-distorting wave,—*b* and *d* shape factors which may be added without producing distortion, the former representing an imaginary and the latter a real value

## ANALYSIS OF CARRIER WAVE

The analysis for the carrier-current wave, analogous to the d-c. wave discussed above, is carried out in Appendix IV. There it is shown that when no care is taken to relate the speed of signaling and the carrier frequency there is no longer a simple separation into a shape factor and a discrimination factor, such as was observed in the case of d-c. telegraphy. The expression for the sinusoidal components is:

$$A_n - i\,B_n = F'(\omega)\,(C_n' - i\,S_n') + F''(\omega)\,(C_n'' - i\,S_n'')$$

If, however, the carrier frequency is taken as an even multiple of the speed of signaling, so that the carrier current is proportional to $\cos\,(2\,\pi\,q\,s\,t - \theta)$, where $q$ is even, it is found that

$$C''_n - i\,S''_n = e^{i2\theta}\,(C'_n - i\,S'_n) = e^{i(\pi q/2+\theta)}\,(C_n - i\,S_n)$$

so that

$$A_n - i\,B_n$$
$$= [e^{-i(\pi q/2+\theta)}\,F'(\omega) + e^{i(\pi q/2+\theta)}\,F''(\omega)]\,(C_n - i\,S_n)$$

which may be written

$$A_n - i\,B_n = F(\omega)\,(C_n - i\,S_n)$$

where $C_n$ and $i\,S_n$ have the same values as in the direct-current case.

$F(\omega)$ is, of course, different in the present case and depends among other things on the phase of the carrier wave at the beginning of the signal element. More specifically the value of the shape factor is given by the expressions:

$$F(\omega) = e^{-i(\pi q/2+\theta)}\,F'(\omega) + e^{i(\pi q/2+\theta)}\,F''(\omega)$$

$$F'(\omega) = \frac{4\,s\sin\,(\omega_c - \omega)/4\,s}{\omega_c - \omega}$$

$$F''(\omega) = \frac{4\,s\sin\,(\omega_c + \omega)/4\,s}{\omega_c + \omega}$$

It is shown in Appendix IV that when the carrier frequency is an odd multiple of the speed of signaling, $(A_n - i\,B_n)$ takes on a slightly different form. However, the following discussion applies equally well whether $q$ is odd or even.

$F'(\omega)$ represents two bands symmetrical about the carrier frequency, each being identical except for sign with the band determined for the direct-current cases. $F''(\omega)$ is a non-symmetrical band and interferes with the symmetry between the upper and lower sidebands. It is shown in Appendix IV that this factor is due to the presence of components higher than the carrier frequency in the modulating wave. Hence, one method of suppressing this factor, and keeping the sidebands symmetrical, is to remove these components from the modulating wave before modulation takes place. A second method of making the shape factor symmetrical is to use an equalizing device, which is so designed as to multiply each component by the ratio

$$\frac{F'(\omega)}{F'(\omega) + e^{i2\theta}\,F''(\omega)}$$

Finally it should be noted that if the band width is small in comparison with the carrier frequency, $F''(\omega)$ is small in comparison with $F'(\omega)$ and, therefore, substantial symmetry is obtained without any special precautions.

If the two sidebands are symmetrical, corresponding frequencies equidistant from the carrier frequency combine to form a wave whose frequency is equal to the carrier frequency and whose envelope is a sine wave corresponding to a component in the direct-current case. The frequency of the envelope equals the difference in frequency between the carrier frequency and that of each of the components forming the pair. On account of the mutual redundance of the two sidebands, the total frequency range required in the symmetrical carrier case (*i. e.*, in the case where the carrier frequency is located in the middle of the transmitted range) for a given speed of signaling is just twice that required in the direct-current case. Except for this, the results as to band width required, and ideal shape factors for the received wave, are the same as obtained above for the direct-current case and it is not necessary to repeat them.

It is obvious that this type of carrier telegraph is relatively inefficient in its utilization of the available frequency range, and it becomes of great interest to inquire how this condition may be improved. An obvious thought is to move the carrier frequency toward one edge of the available band and to increase the speed of signaling in proportion to the interval between the carrier frequency and the far edge of the transmitted range. If an experiment of this kind is undertaken the outcome will be disappointing, unless certain stringent requirements, (explained below), are met. Far from increasing the speed of signaling, it will usually be found that the relocation of the carrier frequency decreases it. This is more fully explained bleow and in Appendix V.

Examining the symmetrical, carrier wave more closely we find that the redundancy residing in having two symmetrical sidebands gives rise to an important property of the received wave. Its frequency is constant, in the sense that the instants of zero value are spaced at constant intervals. This property will be found to restore the intelligence carrying capacity of a given frequency range to the same point as an equal range used in d-c. telegraphy. Let the received signal be $g\ (t)$ sin $\omega\, t$, where the factor sin $\omega\, t$ expresses the fact that the frequency is constant. Consider a device which has two sets of input terminals and whose response is proportional to the product of the two waves impressed. Let the wave applied to one set be $g(t)$ sin $\omega\, t$, and let the other applied wave be sin $\omega\, t$. Then the average response over a cyle is well known to be proportional to $g(t)$, *i. e.*, the envelope. If the second applied wave is cos $\omega\, t$, the average response over a cycle is zero. There are various devices whose response is proportional to the product of two inputs. For the purposes of this paper it will be convenient to think of a dynamometer with one fixed and one movable coil.

*Phase Discrimination.* Systems of telegraphy based on these principles, which may be called phase discrimination systems, have been proposed. Two carrier currents are provided, one of which may be represented by sin $\omega\, t$ and the other by cos $\omega\, t$. Each of these is then modulated in accordance with a separate signal, and the mixture of the signals is impressed on the line. At the receiving end the composite signal wave is impressed on each of two dynamometers whose other windings are energized by currents of the values sin $\omega\, t$ and cos $\omega\, t$, respectively. Thus one dynamometer responds to each signal and there is substantially no mutual interference.

It is clear that in this system the total amount of intelligence transmitted for a given band width is twice as great as for the symmetrical carrier case which does not utilize phase discrimination and is, in fact, the same as for the direct-current case.

*Single Sideband Transmission.* We are now in position to take up the single sideband case. In Appendix V, it is shown that when the carrier frequency is removed from the center of the transmitted band the received wave may be considered to be made up of three component waves. The first of these is an in-phase wave and builds up in the same manner as does a d-c. wave in a low-pass system having a band width equal to the distance from the carrier frequency to the far edge of the transmitted band. This is obviously the wave which we are trying to obtain; and if it existed by itself, the problem would be solved and the experiment referred to above would be successful. The second wave is also in-phase but builds up at a slower rate, namely, that corresponding to the distance from the carrier frequency to the nearer edge of the transmitting band. Since these components are in phase they add algebraically at any given time and it is obvious that the time of building up will tend to be determined by the slower component. Hence, the normal result of moving the carrier from the middle is a slowing up rather than the reverse. Besides, there is the third component wave. This is a quadrature component which is determined in magnitude and rate of building by the frequency band, by which the seperation of the carrier and the far sideband exceeds the separation between the carrier and the near edge. This component, moreover, does not build up to the signal wave, but rather to something approximating the first derivative of the signal envelope. It is clear that the second and third components must both be eliminated. In addition, there is an important condition as to phase correction. Ordinary filters are subject to considerable phase distortion in the vicinity of the edges of the transmitted band. It is of importance that this phase distortion be corrected by suitable means. The problem of single sideband transmission may now be separated into three parts.

1. Phase correction.
2. Elimination of the quadrature component, being the third component discussed.
3. Elimination of the sluggish in-phase component, being the second component discussed.

The first of these problems, the design of phase-correcting networks, does not come within the scope of the present paper. The second part of the problem, the elimination of the quadrature component, is solved by the methods of phase-discrimination telegraphy described above. The third part of the problem, the elimination of the sluggish in-phase component, is solved by moving the carrier so far toward the edge that it disappears. The exact requirements to be met are set forth in the appendix.

## GENERALIZED WAVE FORM

Two kinds of impressed wave forms have been discussed, the rectangular, used in d-c. telegraphy, and the sinusoidal, used in carrier telegraphy. It is of interest to generalize the treatment of impressed waves to cover any other wave form which may be considered, and to include these two as special cases. The restriction will be imposed that the successive signal elements are alike, except for a constant factor which is given the values, $a_1$, $a_2$, etc., for the various signal elements. There is no need to confine the elements to a single time unit. It may overlap into neighboring time units. To facilitate visualizing the wave, Fig. 4 is drawn, which indicates how an impressed wave may overlap both antecedent and subsequent elements. Mathematically it may be expressed by saying that the contribution made by the $h$th signal element to the impressed wave is given by the expression

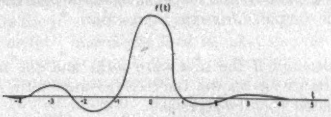

FIG. 4—SPECIMEN OF GENERAL WAVE FORM

$$I_h = a_h f(t)$$

where $f(t)$ is an arbitrary function of the time $t$, whose origin is conventionally taken at the center of the signal element in question. It will be remembered that $a_h$ is called the *magnitude factor* and $f(t)$ the *wave form*. Incidentally, the assumption that the wave form is the same from element to element, excludes the carrier waves where the carrier frequency is not an even multiple of the speed of signaling. We may, therefore, expect to avoid some of the complications which arose in the analysis of those waves. The total wave at any given time is, of course, the algebraic sum of all the components existing at that time.

$$I = I_1 + I_2 + I_3 +, \text{etc.}$$

The Fourier analysis is given in Appendix VI. It is there shown that the sinusoidal components are given by the expression

$$A - i B = F \cdot (C - i S)$$

In other words, there is still the simple separation into two factors, the shape factor and the discrimination factor. The latter is identical with that obtained in the previous cases. The shape factor is determined from the known value of $f(t)$ by the expression

$$F(\omega) = 4 s \int_{-\infty}^{+\infty} f(t)\, e^{-i\omega t}\, d t$$

Now it will be recalled that the shape factor of the received wave is given by the expression

$$F_r = Y F_s$$

and in our previous work, we have evaluated $Y$, the transmission characteristic of the circuit, so as to obtain a desired value of $F_r$ for a given $F_s$. In other words, a desired received current is obtained with a given sent wave by means of circuit design. The present results suggest that the desired $F_r$ can be partly obtained by modifying $F_s$ as well; in other words, the desired received current can be obtained in part by circuit design and in part by signal shaping at the transmitting end.

While signal shaping and equalizing are equivalent it does not follow that they are equally practicable. It may be said that under usual conditions the use of networks is the simpler when only moderate accuracy is required; whereas, the use of signal shaping provides the greater accuracy but is complicated.

There is an infinite number of sent waves which result in non-distorting received waves. Thus it is, for instance, permissible to use a sent signal element consisting of a succession of rectangular waves such as shown in Fig. 9; provided the intervals between changes are not made too great. The calculations for this case are given in Appendix VII.

In the introductory part of the paper mention was made of the fact that the design of equalizers would not be covered. It was also stated that a method of signal shaping would be discussed, which would make up for the resulting incompleteness of the theory. The discussion of the present section, together with Appendix VII, in the matter there referred to.

## DUAL ASPECT OF SIGNALING WAVE

It will be apparent from what has preceded that there are two distinct methods of specifying the wave. One method is based on the time $t$ as the independent variable. This aspect, which may be referred to as *progressive*, contemplates the signaling wave as a succession of signal elements following one another at constant intervals of time from the first to the $N$th. The other aspect which may be called the *cyclical* aspect, is based on $\omega$ as the independent variable. This contemplates the signaling wave as the sum of direct current and a succession of sinusoidal components beginning with the fundamental and including harmonics at least up to the $N/2$th. In the cyclical aspect, it is necessary to know only the magnitude and phase of the successive components. It does not matter in specifying the signal what time it took to transmit the signal. It may be of some economic interest to know how rapidly the signal is transmitted, but from a technical standpoint, $t$ is very much in the background. Analogously, with the *progressive* aspect of the wave the frequency is very much in the background. It is not required to specify the wave, but is of economic interest, in the sense that it is of interest to know the frequency range required for transmission.

An enumeration will now be made of analogous processes and quantities under the two aspects. The *signal element* is the unit out of which the signal is made up when considered as a progressive wave; when considered as a cyclical wave the corresponding elementary unit is the *sinusoidal component*. The signal element has been denoted by $I_h$ and the whole wave by $I = \Sigma I_h$: The sinusoidal component is specified by $A_n$ and $B_n$ and the whole wave by $I = \Sigma (A_n \cos npt + B_n \sin npt)$. The intelligence transmitted is specified in the cyclical aspect by the *discrimination factor*, $C_n - i S_n$; in the progressive aspect this office is taken by the *magnitude factor* $a_h$.

The *wave form* $f(t)$ specifies the shape, or form, of the signal element and includes the degree of deformation. The analog in the cyclical case is the *shape factor* $F(\omega)$. The alteration in the wave, which is caused by the circuit or any circuit part, is specified in the cyclical aspect by the phase and magnitude changes; and to be definite, it may be taken as the *transfer admittance*, $Y(\omega)$, which is a function of $\omega$, and which may be defined as the wave (specified as to magnitude and phase) resulting at the driven point due to impressing a unit sinusoidal wave at the driving point. The analog in the progressive case is the *indicial* admittance, $A(t)$, which may be defined to be the wave as a function of $t$, resulting at the driven point from suddenly impressing a unit wave (constant) at the driving point.

In order to change from one method of consideration to the other, it is desirable to have available equations for changing from the set of quantities suitable for one method to the set suitable for the other. These equations fall into three groups. The first relates the wave form and the shape factor, the quantities which define the type of wave used. The second relates the discrimination factor and the magnitude factor, the quantities which define the particular signal. The third relates the transfer admittance and the indicial admittance, the quantities which define the effect of the circuit on the signaling wave.

The equations are:

$$F(\omega) = 4s \int_{-\infty}^{+\infty} f(t)\, e^{-i\omega t}\, dt$$

$$f(t) = \frac{1}{8\pi s} \int_{-\infty}^{+\infty} F(\omega)\, e^{-i\omega t}\, d\omega$$

$$C_n - i S_n = \frac{1}{N} \sum_{h=1}^{N} a_h\, e^{-i(2\pi n/N)\,(h-1/2)}$$

$$a_h = \sum_{n=-N/2}^{N/2-1} (C_n - i S_n)\, e^{i2\pi n\,(h-1/2)/N}$$

$$Y(\omega) = -\int_{-\infty}^{+\infty} i\,\omega\, e^{-i\omega t} A(t)\, dt$$

$$A(t) = \frac{Y(0)}{2} + \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{Y(\omega)\, e^{i\omega t}}{i\,\omega}\, d\omega$$

Negative values of the argument $\omega$ do not require the conception of negative frequencies. The frequency may be thought of as signless and as represented by positive and negative values of $\omega$ or both.

With either set of quantities, given, or found by the equations, it is possible to make corresponding computations in the two systems. For instance, when the shape factor of the sent wave and the transfer admittance are known, the shape factor of the received wave can be computed from the expression

$$F_r(\omega) = F_s(\omega)\, Y(\omega)$$

Analogously, if the sent wave form and the indicial admittance are known, the received-wave form can be computed from the expression

$$f_r(t) = \frac{d}{dt} \int_{-\infty}^{+\infty} A(\lambda)\, f_s(t-\lambda)\, d\lambda$$

or others which are equivalent. Further, if the transmission characteristics of two circuits connected in tandem are known, their combined characteristic can be computed from

$$Y(\omega) = R\, Y_1(\omega)\, Y_2(\omega)$$

in the one system, and from

$$A(t) = R \frac{d}{dt} \int_{-\infty}^{+\infty} A_1(\lambda)\, A_2(t-\lambda)\, d\lambda$$

or an equivalent. $R$ is a constant in these formulas. It is not the purpose of the present paper to go into circuit relations to any greater extent than is necessary to bring out, clearly, the parallelism and respective self-sufficiency of the two systems. For a fuller exposition of the relations between the various functions of $\omega$, the reader is referred to K. S. Johnson's book, "Transmission Circuits for Telephonic Communication" and for a fuller treatment of the functions of $t$ to J. R. Carson's book, "Electric Circuit Theory and the Operational Calculus."

The formulas shown in the last paragraph indicate that the fundamental parallelism between the two kinds of functions extends to calculations of the received wave. There is a difference, which is not of great significance from the standpoint of pure theory, but which is important from the standpoint of practical computation. It is seen that in the case of functions of $\omega$ the operations consist of the multiplication of two characteristics. In fact, by expressing the characteristic in terms of a logarithmic function of $Y$ in the usual manner, it is possible to reduce these operations to additions. In the case of the functions of $t$ the computations are much more complex involving differentiation, the multiplication of two functions, and the the evaluation of an integral. The processes of differentiation and integration, are, in general, essentially graphical operations which cannot be carried out with the same precision as processes which are essentially arithmetical. It is, therefore, as a practical matter, greatly advantageous to arrange the calculations so they can be carried out with functions of $\omega$.

The important fact is that for telegraph purposes the two methods are substantially equivalent in result, though different in processes and labor involved. The fundamental reason for this difference is that, on the theory as developed in the paper, it is not necessary to compute the received wave as a function of $t$.[5]

The method of analysis used in this paper is that of the Fourier series. It should be mentioned at this point that there is an alternative method, known as that of the Fourier integral. The Fourier integral can be made to yield essentially the same mathematical formulas as have been obtained in this paper. Also, if care is taken, it is possible to obtain essentially the interpretations here given. Appendix IX sets forth the relation between the series and the integral, and points out the problems where special care is needed in applying the integral.

## INTERFERENCE

So far it has been assumed that the circuit is free from external interference. In any actual case there is always some interference present, and it is necessary to take it into account. The effect of the interfering wave is to superpose itself on the singaling wave and give the resultant received wave a different value, which otherwise it would not have. If the interference is great enough, the received wave will be interpreted as different from that intended. If the interference is non-predictable, (as likely to be positive, as negative), its arithmetical value must be less than one-half the difference between any two current values employed in signaling. In fact, the number of distinct magnitude factors, hence, the amount of intelligence that can be transmitted over a circuit, are definitely limited by the interference. It is, therefore, important to consider the nature of the interference and to determine to what extent, if at all, it may be overcome.

Interference may be of many kinds and sources, including such telegraph currents as cross-fire and duplex unbalance. We shall go a step further and consider as interference such portions of the telegraph wave as result from departure from the ideal of the telegraph current. Thus the difference between the actual wave and the desired ideal wave is interference. It is realized that this convention is not in agreement with common usage but, for the purposes of this paper, it is justified by the simplification which results. In order to distinguish this interference from other forms it may be called the *characteristic* interference. The term *intersymbol* interference has also been used for this effect. It is closely related to characteristic distortion.[6]

Interference may usually be reduced by suitable means: Duplex unbalance currents may be reduced by improving the balance; characteristic interference may be reduced by improving the transmission characteristic; and interference from other circuits reduced by decreasing the coupling. But when everything practicable has been done to reduce the interference, there is, in general, a residual left which produces distortion in the signals. The total amount of interference sets a limit to the number of distinct magnitude factors which may be employed and, therefore, to the rate with which intelligence may be transmitted over the circuit. The interference which can be tolerated depends on the amount of energy in the signaling current. This is again limited by the power-carrying capacity of the line, either because certain apparatus overloads or because interference into other circuits becomes too great.

It is of considerable interest to determine the spectral distribution of power in the signal which is most suitable for overriding a given interference. The assumption will be made that the maximum power is definitely limited. It is shown in Appendix VIII that when the shape factor is a constant from zero to the frequency $s$ and zero for other frequencies, the mean total power is proportional to

$$\frac{1}{N}\sum_{k=1}^{N} a_k^2$$

and it follows that for this case all signals which are made up of the extreme values of the magnitude factors, (it is assumed that the positive and negative values are numerically equal), load up the system to the same extent. If some other shape factor were used it would, in general, result in the maximum power only for the most favored signal combination; for others, the power would be less. It is concluded that for the purpose of overriding interference, when the power carrying capacity of the line is the limiting factor, the shape factor just considered is the most suitable at the point where the interference is introduced.

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[5] *Submarine Cable Telegraphy*, J. W. Milnor, A. I. E. E. TRANSACTIONS, Vol. 41, p. 20; in particular the suggestion made in the closing paragraph on p. 38.

[6] *Measurement of Telegraph Distortion*, Nyquist, Shanck and Cory, A. I. E. E. JL., Vol. 46, p. 231, 1927.

In discussing the interference above, it has been assumed that the circuit is linear. If some of the circuit elements are non-linear, the result may be looked on as interfering currents generated in the elements. This interference is predictable and it is theoretically possible to eliminate or reduce it by introducing elements which produce a compensating distortion.

The assumptions have been made that the signal elements are all of equal duration and that the system is designed especially to handle signal elements of that specific duration. In other words, the system is designed for a given speed of signaling in preference to other speeds, both slower and faster. It is of obvious interest to inquire what the effect is when the speed is somewhat different from that for which the system has been designed, the signal elements being of equal length.

Suppose a system is designed to be distortionless at a speed of signaling $s$, and suppose that it is used to transmit signals of the speed $\gamma s$, where $\gamma$ is a factor which does not differ greatly from unity. Let the system be such that the admittance is given by

$$Y(\omega)\ (\cos \omega \tau - i \sin \omega \tau)$$

An admittance which would give distortionless transmission at the speed of $\gamma s$ is then given by the expression

$$Y(\omega/\gamma)\ (\cos \omega \tau - i \sin \omega \tau)$$

The difference between the actual admittance given by the first expression and the ideal admittance given by the second expression represents an admittance giving rise to interfering currents. Neglecting the constant delay, this admittance is given by the expression

$$Y(\omega) - Y(\omega/\gamma)$$

and the current corresponding to this admittance is the portion of the characteristic interference which arises from the alteration in speed.

Formulas for the interfering wave may be deduced from this expression, but it will be sufficient for our purposes to note the ratio of the interfering wave to the signaling wave at a specific frequency. This ratio is given by the expression

$$\frac{Y(\omega) - Y(\omega/\gamma)}{Y(\omega)}$$

or approximately

$$\frac{(\omega - \omega/\gamma)}{Y(\omega)} \cdot \frac{d\,Y}{d\,\omega} \quad .$$

It will be seen that for a small discrepancy between the ideal speed and the actual speed the amount of distortion is largely determined by the slope of the transfer admittance curve. The more abruptly the transfer admittance changes, the greater will be the interference accompanying a small change in signaling speed.

It has been assumed that the change of speed is uniform, *i. e.*, that all signal elements are lengthened or shortened in the same proportion. It is of considerable practical interest to inquire what happens when there is no such regularity in the change of speed, in other words, when some signal elements are shortened and some are lengthened and when the various elements are not changed in the same proportion. Consider first a signal consisting of a single element of finite current value, the current values of the remaining signal elements being zero. It is clear that it makes no difference where the ends of the signal elements are taken when the current value is zero, and consequently this particular signal may be considered to come under the case already discussed. In other words, the interference due to any one element is as discussed above. Further, the total interfering current at any instant is the sum of the interference caused by all the elements. It follows that to a first approximation, the interference is the same as that deduced above for the regular lengthening or shortening.

It has been indicated that if interference from foreign sources is kept low, the transfer admittance made to comply with certain requirements and the speed of signaling kept constant, it is possible to transmit signals with very little distortion, utilizing a frequency range which is only slightly greater than the speed of signaling. One advantage of keeping the distortion small is that a large number of current values may be employed, thus increasing the intelligence-carrying capacity of the line. As explained above, the total interfering current should be less than one-half the difference between adjacent current values. In actual practise it will probably be found desirable to keep considerably within these limits, so as to have a definite margin. On the other hand, there would be no object in reducing the interference beyond the point where the signal is decipherable with certainty and ease.

## Appendix I.

*Analysis of D-C. Wave.* It is required to find the sinusoidal components of a telegraph wave of $T$ sec. duration composed of $N$ rectangular signal elements and repeated an indefinitely great number of times. Let the value of the wave at any instant be denoted by $E(t)$, where

$E(t) = a_1$ for $0 < t < T/N$, (time unit 1),
$E(t) = a_2$ for $T/N < t < 2\,T/N$, (time unit 2),
$E(t) = a_h$ for $(h-1)\,T/N < t < h\,T/N$, (time unit $h$).

Represented as a Fourier series the wave is

$$E(t) = \frac{A_0}{2} + \sum_{n=1}^{\infty} (A_n \cos npt + B_n \sin npt), \qquad (1)$$

where $p/2\,\pi = 1/T$ is the frequency of the fundamental wave. The problem is to find expressions for the $A$'s and $B$'s, so they can be computed from the known values of the $a$'s.

Multiply both sides of the equation by $\cos kpt\,dt$ and integrate from zero to $T$. In this expression $k$ is a positive integer.

$$\int_0^T E(t)\cos kpt\,dt = \frac{A_0}{2}\int_0^T \cos kpt\,dt + \sum_{n=1}^{\infty} A_n \int_0^T \cos kpt \cos npt\,dt + \sum_{n=1}^{\infty} B_n \int_0^T \cos kpt \sin npt\,dt, \tag{2}$$

From a well-known trigonometric formula

$$\cos kpt \cos npt = \frac{\cos (k+n)\,pt + \cos (k-n)\,pt}{2}.$$

The integration is carried out over an integral number of cycles and the result is, therefore, equal to zero with the single exception where $n = k$ when the integrand has the average value 1/2 and the integral is $T/2$. Likewise,

$$\cos k\,p\,t \sin n\,p\,t = \frac{\sin (k+n)\,p\,t - \sin (k-n)\,p\,t}{2}$$

The integrals of these obviously are also zero. The right member of equation (**2**) reduces, therefore, to the single term

$$A_k\,T/2.$$

The left member of equation (**2**) may be written

$$a_1\int_0^{T/N}\cos kpt\,dt + a_2\int_{T/N}^{2T/N}\cos kpt\,dt + \text{etc.}$$

or

$$\sum_{h=1}^{N} a_h \int_{(h-1)T/N}^{hT/N}\cos kpt\,dt\,.$$

Changing the origin of $t$ to the center of the time unit to which each integral refers, *i. e.*, putting

$$t = (h - 1/2)\,T/N + t'$$

and dropping the prime, we have

$$\sum_{h=1}^{N} a_h \int_{-T/2N}^{T/2N}\cos\left[k\left(h-\frac{1}{2}\right)\frac{T}{N}\,p + kpt\right]dt$$

$$= \sum_{h=1}^{N} a_h\left[\cos k\left(h-\frac{1}{2}\right)\frac{T}{N}\,p\int_{-T/2N}^{T/2N}\cos kpt\,dt - \sin k\left(h-\frac{1}{2}\right)\frac{T}{N}\,p\int_{-T/2N}^{+T/2N}\sin kpt\,dt\right].$$

The integral in the second term is equal to zero. Rearranging and substituting $n$ for $k$, this expression becomes:

$$\int_{-T/2N}^{T/2N}\cos npt\,dt\sum_{h=1}^{N} a_h\cos n\left(h-\frac{1}{2}\right)\frac{T\,p}{N} = \frac{A_n\,T}{2}. \tag{3}$$

The value of the integral is:

$$\frac{2\sin npT/2\,N}{np}.$$

Remembering that $T\,p = 2\,\pi$, $N/2\,T = s$, the speed of signaling, and $np = 2\,\pi\,n/T = \omega$, the result becomes

$$\frac{A_n\,T}{2} = \frac{2\sin\,\omega/4\,s}{\omega}\sum_{h=1}^{N} a_h\cos\frac{2\,\pi\,n}{N}\left(h-\frac{1}{2}\right)$$

or

$$A_n = \frac{8\sin\,\omega/4\,s}{\omega/s}\,\frac{1}{N}\sum_{h=1}^{N} a_h\cos\frac{2\,\pi\,n}{N}\left(h-\frac{1}{2}\right). \tag{4}$$

This has now been established for all values of $n$ except zero. If the same procedure be gone through with equation (**1**) without multiplying by $\cos kpt$ it will be found that this formula does in fact hold for $A_0$ as well. Further, if equation (**1**) be multiplied by $\sin kpt$ and the same operations are performed it will be found that

$$B_n = \frac{8\sin\,\omega/4\,s}{\omega/s}\,\frac{1}{N}\sum_{h=1}^{N} a_h\sin\frac{2\,\pi\,n}{N}\left(h-\frac{1}{2}\right). \tag{5}$$

Put

$$F(\omega) = \frac{8\sin\,\omega/4\,s}{\omega/s}, \tag{6}$$

$$C_n = \frac{1}{N}\sum_{h=1}^{N} a_h\cos\frac{2\,\pi\,n}{N}\left(h-\frac{1}{2}\right) \tag{7}$$

$$S_n = \frac{1}{N}\sum_{h=1}^{N} a_h\sin\frac{2\,\pi\,n}{N}\left(h-\frac{1}{2}\right), \tag{8}$$

The expressions (**4**) and (**5**) may now be written

$$A_n - i\,B_n = F(\omega)\,(C_n - i\,S_n) \tag{9}$$

The function $F$ is determined by the wave form and $(C_n - i\,S_n)$ by the intelligence being transmitted. The former will be called the shape factor, the latter the discrimination factor.

It is a matter of convention whether a plus or minus sign is chosen in equation (**9**). The choice made is consistent with the more usual convention.

## Appendix II-A

*Specific Criterion of Distortionless Transmission.* It is of interest to investigate how intelligence may be accurately transmitted by signals employing rectangular wave shape at the sending end with a minimum frequency band width. In Fig. 1 it is indicated that this is usually possible when a band width equal to $s$ is transmitted. A case of practical importance is where frequencies are transmitted from zero up to the speed of signaling. When such a limited frequency range is employed the received wave is, of course, different from the sent wave. In order that the received wave convey intelligence, it is sufficient that something pertaining to the wave in each of its time units be proportional or equal to the magnitude factor of each signal element at the sending end. First, let it be assumed that the received wave at the middle of each time unit, measured by an ideal receiving device, be representative of the signal element sent during that time unit. No notice will be taken of the wave at any other point in the time unit, and consequently deformations of the wave at other points will not matter. It will be computed below what shape factor the received wave must have in order for its value at the middle of each time unit to equal the corresponding amplitude of the sent wave.

Let the current at the receiving end at the middle of the time unit, $h$, be equal to $a_h$. Now $t = (h - 1/2)T/N$ at the middle of the time unit, and the Fourier series becomes:

$$a_h = \frac{A_0}{2} + \sum_{n=1}^{N/2} \left[ A_n \cos \frac{2\pi n}{N}\left(h - \frac{1}{2}\right) + B_n \sin \frac{2\pi n}{N}\left(h - \frac{1}{2}\right)\right]. \tag{1}$$

There are $N$ such equations, since $h$ may successively take the values 1, 2 . . . $N$. There are also $N$ unknown values of $A$'s and $B$'s. (Note, $B_0 = 0$ and $A_{N/2} = 0$.) These unknowns may be determined by the usual methods of solving simultaneous equations, or more simply in the following manner: Multiply all equations from $h = 1$ to $h = N$ by $\cos \frac{2\pi k}{N} h - \left(\frac{1}{2}\right)$ and add them:

$$\sum_{h=1}^{N} a_h \cos \frac{2\pi k}{N}\left(h - \frac{1}{2}\right) \overset{(a)}{= \frac{A_0}{2} \sum_{h=1}^{N} \cos \frac{2\pi k}{N}\left(h - \frac{1}{2}\right)}$$
$$\overset{(b)}{+ \frac{1}{2} \sum_{h=1}^{N} \sum_{n=1}^{N/2} \left\{ A_n \left[ \cos (n+k) \frac{2\pi}{N}\left(h - \frac{1}{2}\right)\right.\right.} \overset{(c)}{\left.+ \cos (k-n) \frac{2\pi}{N}\left(h - \frac{1}{2}\right)\right]}$$
$$\overset{(d)}{+ B_n \left[ \sin (n+k) \frac{2\pi}{N}\left(h - \frac{1}{2}\right)\right.} \overset{(e)}{\left.\left. - \sin (k-n) \frac{2\pi}{N}\left(h - \frac{1}{2}\right)\right]\right\}}. \tag{2}$$

In equation (**2**), use has been made of the trigonometric formulas:

$$\cos a \cos b = \frac{\cos (a+b) + \cos (a-b)}{2}$$

$$\cos a \sin b = \frac{\sin (a+b) - \sin (a-b)}{2}$$

In order to simplify equation (**2**) we will employ the identities:

$$\sum_{h=1}^{N} \cos x \left(h - \frac{1}{2}\right) = \frac{\cos Nx/2 \sin Nx/2}{\sin x/2} \tag{3}$$

$$\sum_{h=1}^{N} \sin x \left(h - \frac{1}{2}\right) = \frac{\sin^2 Nx/2}{\sin x/2}, \tag{4}$$

To prove these identities, multiply the left member of (**4**) by $i$ and add to the left member of (**3**):

$$\sum_{h=1}^{N} \cos \left(h - \frac{1}{2}\right) x + i \sin \left(h - \frac{1}{2}\right) x = \sum_{h=1}^{N} e^{i(h-1/2)x}$$

$$= e^{-\frac{ix}{2}} \sum_{h=1}^{N} e^{ihx} = e^{\frac{ix}{2}}(1 + e^{ix} + e^{i2x} + \; . \; . \; . \; e^{i(N-1)x})$$

$$= \frac{e^{\frac{ix}{2}}\,(1 - e^{iNx})}{1 - e^{ix}} = \frac{e^{\frac{iNx}{2}}\,(e^{-\frac{iNx}{2}} - e^{\frac{iNx}{2}})}{e^{-ix/2} - e^{ix/2}} = \frac{e^{\frac{iNx}{2}} \sin Nx/2}{\sin x/2}$$

$$= \frac{\cos Nx/2 \sin Nx/2}{\sin x/2} + i\,\frac{\sin^2 Nx/2}{\sin x/2}. \tag{5}$$

Equating real and imaginary parts gives equations (**3**) and (**4**), respectively.

By applying formula (**3**) to terms (a), (b), and (c), of equation (**2**), and applying formula (**4**) to terms (d) and (e),

$$\sum_{h=1}^{N} a_h \cos \frac{2\pi k}{N}\left(h - \frac{1}{2}\right) = \frac{A_0}{2}\;\frac{\cos k\pi \sin k\pi}{\sin k\pi/N}$$

$$+\frac{1}{2}\sum_{n=1}^{N/2}\left[A_n\left(\frac{\cos(n+k)\pi\sin(n+k)\pi}{\sin(n+k)\pi/N}\right.\right.$$

$$\left.+\frac{\cos(k-n)\pi\sin(k-n)\pi}{\sin(k-n)\pi/N}\right)$$

$$\left.+B_n\left(\frac{\sin^2(n+k)\pi}{\sin(n+k)\pi/N}-\frac{\sin^2(k-n)\pi}{\sin(k-n)\pi/N}\right)\right]. \quad (6)$$

As $k$ approaches any integral value of $n$, for instance $m$, from 0 to $N/2-1$ inclusive, all the numerators of the terms in the right-hand member of equation (**6**) approach zero. Consequently, these terms approach zero except one term

$$\frac{A_m}{2}\;\frac{\cos(k-m)\pi\sin(k-m)\pi}{\sin(k-m)\pi/N}$$

whose denominator also approaches zero. This term becomes $N A_m/2$. Setting $k = m$, solve equation (**6**) for $A_m$:

$$A_m = \frac{2}{N}\sum_{h=1}^{N} a_h \cos\frac{2\pi m}{N}\left(h-\frac{1}{2}\right) = 2\,C_m. \quad (7)$$

Changing subscripts:

$$A_n = 2\,C_n. \quad (8)$$

Now if, instead, we multiply equation (**1**) by $\sin\frac{2\pi k}{N}\left(h-\frac{1}{2}\right)$, a similar process gives:

$$B_n = 2\,S_n, \qquad (n < N/2). \quad (9)$$

But when $n = N/2$ this process gives:

$$B_{N/2} = S_{N/2}. \quad (10)$$

From equations (**8**) to (**10**) it is seen that the shape factor which will be denoted by $F_0(\omega)$, is equal to 2 from zero frequency up to the speed of signaling where it suddenly drops to half that value. Above this frequency $F_0(\omega)$ is equal to zero, as shown in curve *a*, Fig. 2.

It will next be shown that there is an infinite number of shape factors which may be added to curve *a* which produce no change in the current at the middle of the time units. For example, curve *b* shows a specimen of such a shape factor, which may be any single valued curve so long as it is symmetrical about the speed of signaling except for a change in sign. When this shape factor is added to that of curve *a*, a curve such as *c* may result for the total shape factor which is also ideal. Denote the shape factor of curve *b* by $F_\Delta(\omega)$. The wave, due to such a shape factor, is:

$$\sum_{n=N/2-m}^{N/2+m} F_\Delta(\omega)\,(C_n\cos npt + S_n\sin npt)$$

$$= \sum_{n=0}^{m} F_\Delta(\omega)\,(C_{N/2-n}\cos(2\pi s - n p)\,t$$

$$+ S_{N/2-n}\sin(2\pi s - n p)\,t)$$

$$+ \sum_{n=1}^{m} F_\Delta(\omega)\,(C_{N/2+n}\cos(2\pi s + n p)\,t$$

$$+ S_{N/2+n}\sin(2\pi s + n p)\,t) \quad (11)$$

where $m$ is any positive integer less than $N/2$. It follows from equations (**7**) and (**8**) of Appendix I that:

$$-C_{N/2-n} = C_{N/2+n} \quad (12)$$

$$S_{N/2-n} = S_{N/2+n}. \quad (13)$$

Substitute these relations in equation (**11**) making use of the trigonometric formulas:

$$\cos(a-b) + \cos(a+b) = 2\cos a\cos b \quad (14)$$

$$-\sin(a-b) + \sin(a+b) = 2\cos a\sin b \quad (15)$$

and put $F_\Delta(2\pi s) = 0$ and $F_\Delta(2\pi s + n p) = -F_\Delta(2\pi s - n p)$ so that the formula for the wave becomes:

$$\sum_{n=1}^{m} 2\,F_\Delta(2\pi s + n p)\,(\cos 2\pi s t)\,(C_{N/2+n}\cos npt$$

$$+ S_{N/2+n}\sin npt). \quad (16)$$

Since this expression contains the factor $\cos 2\pi s t$, which is zero at the middle of the time unit, the wave does not have any effect on the receiving device when the latter records current values at the middle of the time units only. The curve *b* is any real shape factor, symmetrical about the dot frequency except for a change in sign. Therefore, every such real shape factor when added to curve *a* gives a resultant shape factor which is ideal.

It is next desired to show that the addition of an imaginary shape factor which is any single valued function whatever, provided it is symmetrical about the dot frequency in both magnitude and sign, does not contribute to the value of the wave at the middle of the time units. Consider the curve *d* of Fig. 2, which represents the magnitude of any symmetrical imaginary shape factor, $i\,F_\Delta(\omega)$.

$$A_n - i\,B_n = i\,F_\Delta(\omega)\,(C_n - i\,S_n) = F_\Delta(\omega)\,(S_n + i\,C_n). \quad (17)$$

Equating real and imaginary parts of equation (**17**) the values of $A_n$ and $B_n$ are determined, so that the wave may be expressed as follows:

$$\sum_{n=N/2-m}^{N/2+m} F_\Delta(\omega)\,(S_n\cos npt + C_n\sin npt)$$

$$= \sum_{n=0}^{m} F_\Delta(\omega)\,(S_{N/2-n} \cos(2\pi s - n p)\,t$$

$$+ C_{N/2-n} \sin(2\pi s - n p)\,t\,)$$

$$+ \sum_{n=1}^{m} F_\Delta(\omega)\,(S_{N/2+n} \cos(2\pi s + n p)\,t$$

$$+ C_{N/2+n} \sin(2\pi s + n p)\,t\,)\,. \qquad \mathbf{(18)}$$

Using formulas (**12**) to (**15**) and putting $F_\Delta(2\pi s + n p) = F_\Delta(2\pi s - n p)$ the wave becomes:

$$\sum_{n=0}^{m} 2 F_\Delta(2\pi s + n p)\,(\cos 2\pi s t)\;(S_{N/2+n} \cos npt$$

$$+ C_{N/2+n} \sin npt), \qquad \mathbf{(19)}$$

which is zero at the middle of the time units on account of the factor $\cos 2\pi s t$. Since this is true for any symmetrical function, $F_\Delta(\omega)$, there is an infinite number of imaginary shape factors which do not affect the values of the wave at the middle of the time units.

## Appendix II-B

*Network for Distortionless Transmission.* The purpose of this appendix is to illustrate, concretely, the matter which has been discussed in Appendix II-A, and the portions of the main text associated therewith. This appendix does not form any part of the chain of reasoning in the sense that anything which is here discussed or deduced will be required subsequently. It can, therefore, be eliminated by those who are primarily interested in the deductions of the main theory.

It has been shown in Appendix II-A that a certain ideal shape factor can be modified by the addition of certain other shape factors which possess a specific kind of symmetry about a frequency equal to the speed of signaling. It is obvious, on consideration, that similar shape factors possessing symmetry about the frequencies 2 *s*, 3 *s*, etc., can also be added in a similar manner without affecting the principal characteristic of the shape factor. These considerations are not of great practical importance in the cases considered because it has been assumed that the important telegraph problem is to transmit maximum intelligence in minimum frequency range. However, these considerations will aid in understanding the subject matter of the present appendix.

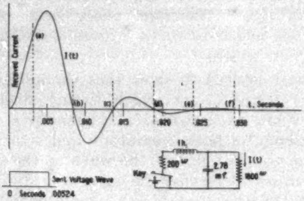

FIG. 5—INSTANCE OF NON-DISTORTING WAVE

Fig. 5 shows a very simple circuit which has been designed for the purpose of illustrating a non-distorting wave. This circuit, containing only two reactance elements, has a very simple form of transient, namely, a uniformly damped sine wave. Now an important property of the sine wave is that its zeros are located at equal intervals, which is precisely the property required of a non-distorting wave under the criterion discussed in Appendix II-A. The interval between successive zeros in the illustration chosen is 0.00524 sec.; and this is also made the duration of the time unit of the sent signal, as illustrated in the figure. It will be remembered that on the criterion under discussion a specific point of the signal element is picked out and taken to represent the element. In the case illustrated, this point should be taken at an interval 0.00524 sec. previous to the first zero. It is obvious that if this is done the interference due to all previous signal elements is zero because the interference due to each one of them is zero. It follows that any receiving device which is made to function by the current at that point will be distortionless as far as interference from adjacent signal elements is concerned.

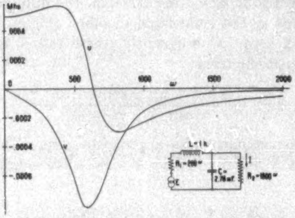

FIG. 6—TRANSFER ADMITTANCE, $u + i\,v$, CORRESPONDING TO THE NON-DISTORTING WAVE SHOWN IN FIG. 5

Fig. 6 shows the transfer admittance of the same network. The speed of signaling corresponds to the point for which the abscissa is 600. It will be observed that these curves do not possess the simple symmetrical characteristics discussed in Appendix II-A, but this is because Appendix II-A was confined to a narrow frequency range not much exceeding the signaling range. If consideration be given to this fact, together with facts discussed in the second paragraph of the present appendix, it will be found that this simple network illustrates the theory.

Both the transfer admittance and the value of the current curve are easily computed in the present case. The transfer admittance is given by the expression:

$$Y = \frac{1}{R_1 + R_2 + i\,\omega\,(L + R_1 R_2 C) - \omega^2 L C R_2}.$$

The current, from the time $t = 0$ up to the time $t = 0.00524$ sec., is given by an expression which takes the following form for the numerical values given:

$$A\,(t) = \frac{1}{2000}\Big[1 - e^{-200t}\Big(\cos 600\,t + \frac{1}{3}\sin 600\,t\Big)\Big].$$

After the time $t = 0.00524$ sec., the current is given by the expression:

$$A\,(t) - A(t - 0.00524)$$
$$= \frac{-\,e^{-200t}}{2000}\Big(1 + e^{1 \cdot 048}\Big)\Big(\cos 600\,t + \frac{1}{3}\sin 600\,t\Big).$$

## Appendix III

*Alternative Criteria of Distortionless Transmission.* An alternative criterion of distortionless transmission is that the interval, between the instants when the received wave passes through the mean value, shall be the same as the corresponding interval at the transmitting end. A receiving device which responds to the values of the wave at the ends of the time units, instead of at the middle, will give distortionless transmission provided the wave at the end of the element, $h$, is proportional to $(a_h + a_{h+1})/2$. This is the criterion in ordinary land-line telegraphy. Strictly speaking, we should also require that the wave does not pass through this value at points located within the time unit. It is thought that the complication involved by introducing this condition is not warranted. We will first determine the coefficients of the Fourier expansion of this received wave for the case where the frequency range is limited to the interval between zero and $s$. We have:

$$\frac{a_h + a_{h+1}}{2} = \frac{A_0}{2} + \sum_{n=1}^{N/2}\Big(A_n \cos\frac{2\,\pi\,n\,h}{N}$$
$$+ B_n \sin\frac{2\,\pi\,n\,h}{N}\Big), \qquad (1)$$
$$(h = 1, 2, \ldots N),$$

since $t = h\,T/N$ at the end of the $h$th time unit.

As in Appendix II-A, we have $N$ simultaneous equations and $N$ unknowns, the $A$'s and the $B$'s. The solution is of the same nature as before, except that the equations are multiplied by $\cos\frac{2\,\pi\,k\,h}{N}$ instead of $\cos\frac{2\,\pi\,k}{N}\Big(h - \frac{1}{2}\Big)$, before being summed. For values of $n < N/2$ we find by similar reasoning:

$$A_n = \frac{2}{N}\sum_{h=1}^{N}\frac{a_h + a_{h+1}}{2}\cos\frac{2\,\pi\,n\,h}{N}$$

$$= \frac{1}{N}\sum_{h=1}^{N} a_h\Big[\cos\frac{2\,\pi\,n\,h}{N} + \cos\frac{2\,\pi\,n\,(h-1)}{N}\Big]. \qquad (2)$$

By means of the trigonometric formula

$$\cos a + \cos b = 2\cos\frac{1}{2}\,(a + b)\cos\frac{1}{2}\,(a - b)$$

we find that equation (2) may be written:

$$A_n = \frac{2}{N}\Big(\cos\frac{n\,\pi}{N}\Big)\sum_{h=1}^{N} a_h \cos\frac{2\,\pi\,n}{N}\Big(h - \frac{1}{2}\Big)$$

$$= 2\cos\frac{\omega}{4\,s}\,C_n \qquad (3)$$

An analogous line of reasoning gives:

$$B_n = 2\cos\frac{\omega}{4\,s}\,S_n. \qquad (4)$$

The shape factor is $2\cos\omega/4\,s$ (Fig. 3, curve $a$), for frequencies up to $s$, and remains zero for higher frequencies. A transfer admittance which will produce a wave of this form when the sent wave is rectangular is:

$$Y = \frac{\omega}{4\,s}\cot\frac{\omega}{4\,s}, \text{ when } \omega < 2\,\pi\,s \qquad (5a)$$

$$Y = 0, \qquad \text{when } \omega \geq 2\,\pi\,s. \qquad (5b)$$

This is obtained from the ratio of the shape factor at the receiving end, divided by the shape factor at the sending end.

Such a system would be incapable of transmitting ordinary reversals, since zero current is transmitted for frequencies equal to or greater than the dot speed. This defect may be remedied by the addition of shape factors which are symmetrical about the signaling frequency, and do not contribute anything to the wave at the ends of the time units. By reasoning, analogous to that given at the close of Appendix II-A, it follows that the wave due to any real shape factor, symmetrical about the speed of signaling in magnitude and sign, (Fig. 3, curve $d$), contains the factor $\sin 2\,\pi\,s\,t$, and, therefore becomes zero at the ends of the time units. In a similar manner it can be shown that the wave due to any imaginary shape factor, symmetrical about the dot frequency in magnitude but not in sign, (Fig. 3, curve $b$), also becomes zero at the ends of the time units. The addition of curve $d$ to curve $a$ gives curve $c$, which is also an ideal shape factor.

A third criterion for distortionless transmission is that the area under the received wave shall have the same value as that under the sent wave during each time unit. Thus during the time unit $h$, the area under the received wave must be:

$$a_h\,T/N = \int_{t=(h-1)T/N}^{hT/N}\Big[\frac{A_0}{2} + \sum_{n=1}^{N/2}(A_n \cos npt$$

$$+ B_n \sin npt) \Big] dt\,. \tag{6}$$

This equation may be multiplied by $N/T$, integrated, and by means of the trigonometric formulas

$$\sin a - \sin b = 2 \cos \frac{1}{2} (a + b) \sin \frac{1}{2} (a - b)$$

$$- \cos a + \cos b = 2 \sin \frac{1}{2} (a + b) \sin \frac{1}{2} (a - b)$$

it may be reduced to the following form:

$$a_h = \frac{A_0}{2} + \sum_{n=1}^{N/2} \left( \frac{N}{\pi n} \sin \frac{\pi n}{N} \right) \times$$

$$\left[ A_n \cos \frac{2 \pi n}{N} \left( h - \frac{1}{2} \right) \right.$$

$$\left. + B_n \sin \frac{2 \pi n}{N} \left( h - \frac{1}{2} \right) \right] \tag{7}$$

This equation is the same as equation (**1**) of Appendix II-A, except for the factor:

$$\left( \frac{N}{\pi n} \sin \frac{\pi n}{N} \right) = \left( \frac{4 s}{\omega} \sin \frac{\omega}{4 s} \right)$$

Consequently the shape factor for this wave is equal to the shape factor of curve $a$, Fig. 2, divided by $4 s/\omega \sin \omega/4 s$ which reduces to:

$$F_0 (\omega) = \frac{\omega/2 s}{\sin \omega/4 s}, \quad \text{for } 0 \leq \omega < 2 \pi s, \tag{8}$$

$$F_0 (\omega) = \pi/2, \quad \text{for } \omega = 2 \pi s, \tag{9}$$

$$F_0 (\omega) = 0, \quad \text{for } 2 \pi s < \omega, \tag{10}$$

which, if the sent wave is rectangular, corresponds to a transfer admittance:

$$Y (\omega) = \left( \frac{\omega/4 s}{\sin \omega/4 s} \right)^2, \quad \text{for } 0 \leq \omega < 2 \pi s, \tag{11}$$

$$Y (\omega) = \frac{\pi^2}{8}, \quad \text{for } \omega = 2 \pi s, \tag{12}$$

$$Y (\omega) = 0, \quad \text{for } 2 \pi s < \omega\,. \tag{13}$$

In order to determine shape factors which may be added to $F_0 (\omega)$ without changing the received signal, the following method may be employed. Let $F_\Delta (\omega)$ represent the shape factor to be added. The wave due to this shape factor comprises frequency components which lie above and below the dot speed. Let $\delta$ equal any convenient frequency increment not greater than $s$. Then consider any pair of components at the frequencies $(s + \delta)$ and $(s - \delta)$, respectively, and find what values of $F_\Delta (\omega)$ at these frequencies will produce components which do not change the received signal. The portion of the wave due to these components is:

$$\begin{aligned} I = F_\Delta (2 \pi (s - \delta)) & (C_{N/2-n} \cos 2 \pi (s - \delta) t \\ & + S_{N/2-n} \sin 2 \pi (s - \delta) t) \\ + F_\Delta (2 \pi (s + \delta)) & (C_{N/2+n} \cos 2 \pi (s + \delta) t \\ & + S_{N/2+n} \sin 2 \pi (s + \delta) t) \end{aligned} \tag{14}$$

In order that this portion of the wave add nothing to the received signal, $\int I\, dt$ must be zero between $h/2 s$ and $(h - 1)/2 s$, which is the time of the unit $h$. Performing the integration and simplifying the result gives an expression which reduces to zero when

$$F_\Delta (2 \pi (s - \delta))/(s - \delta) = - F_\Delta (2 \pi (s + \delta))/(s + \delta) \tag{15}$$

Thus $F_\Delta (\omega)$ may have any real value, provided the conditions of symmetry are fulfilled as expressed in equation (**15**). This is true for any value of $\delta < s$, and, therefore, is true for all values of $\delta < s$. A similar line of reasoning for imaginary shape factors, $i F_\Delta (\omega)$, which do not change the signal, gives:

$$i F_\Delta (2 \pi (s - \delta))/(s - \delta) = i F_\Delta (2 \pi (s + \delta))/(s + \delta). \tag{16}$$

*Insufficiency of Ranges Smaller than the Signaling Speed.* It has been shown that a frequency range numerically equal to the speed of signaling is necessary for the case where there is no limitation on the number of distinct magnitude factors. It might be questioned whether the proposition is true when this number is small. Consider the case where there are just two, distinct magnitude factors, + 1 and − 1, and where the current at the middle of the time units is taken as the criterion of transmission. Since there are only two magnitude factors involved it is to be considered necessary and sufficient that the wave at the mid-point of each time unit should have the proper sign, regardless of magnitude. We will now show that this cannot be insured when the transmitted range is less than the speed of signaling.

Suppose first that the transmitted range extends from zero to a point lower than the speed of signaling, so that the missing portion is at the upper end of the range $0 - s$. Let $N/2$ be an odd number and let the first $N/2$ signal elements be $+ - + - \ldots\ldots\ldots - +$. Let the next $N/2$ signal elements be a repetition of this and let the signal be repeated indefinitely. By far the most important harmonic of this signal below the frequency $s$ is the $(N/2 - 1)$th which corresponds to a frequency of $s\,(1 - 2/N)$. By taking $N$ sufficiently large we can insure that this harmonic is suppressed. If all frequencies up to $s$ are transmitted and equalized for distortionless transmission, and then the frequency $s\,(1 - 2/N)$ removed, it is found that, due to the great magnitude of this component, the signal is reversed in sign at some of the critical points (mid-points). The question is, whether by alteration of the remaining components this can be corrected. We next show that this cannot be done.

Consider the function $\cos 2 \pi s\,(1 - 2/N)\,t$. (This function has the same sign as the sent signal at all the critical points.) Next consider the sum obtained by adding the products of this function and the received wave value at the critical points. If the wave is correct in sign each one of these products is positive and therefore the sum is positive. Now, it is easy to show that for any component of the received wave of lower frequency than $s\,(1 - 2/N)$, the contribution to this sum is zero, the negative products balancing the positive. Therefore the assumption, that the received wave has the correct sign at all the critical points, and the assumption that it is made up entirely of frequencies lower than $s\,(1 - 2/N)$, are inconsistent.

In case the suppressed range is not at the upper end of the range $0 - s$ the procedure is similar. First find a frequency, prime with respect to $s$, and which lies in the suppressed range, and is an even harmonic of the period $T$. Let its frequency be $s'$. Construct the function $\cos 2\,\pi\, s'\, t$. Next construct a signal made up of $+1$ and $-1$ elements whose sign at each critical point is the same as that of $\cos 2\,\pi\, s'\, t$. The argument then proceeds as before.

Similar proofs can be produced for other criteria.

## Appendix IV

*Analysis of Carrier Wave.* It is required to find the sinusoidal components of a carrier-telegraph wave of $T$ sec. duration, composed of $N$ time units, and repeated an indefinitely great number of times. The carrier current is modulated by a rectangular envelope during each of the time units, so that the wave has the following values:

$E\,(t) = a_1 \cos\,(\omega_c\, t - \theta)$, for $0 < t < T/N$, (time unit 1),

$E\,(t) = a_2 \cos\,(\omega_c\, t - \theta)$, for $T/N < t < 2\,T/N$, (time unit 2),

. . . . . . . . . . . . . . .

$E\,(t) = a_h \cos\,(\omega_c\, t - \theta)$, for $(h - 1)\,T/N < t < h\,T/N$, (time unit $h$), etc.

Let the total wave be represented by the Fourier series:

$$\frac{A_0}{2} + \sum_{n=1}^{\infty} (A_n \cos npt + B_n \sin npt)\,. \qquad (1)$$

By reasoning similar to that of Appendix I:

$$A_n = \frac{2}{T} \sum_{h=1}^{N} \int_{(h-1)T/N}^{hT/N} a_h \cos npt \cos\,(\omega_c\, t - \theta)\, dt$$

$$= \frac{1}{T} \sum_{h=1}^{N} \int_{(h-1)T/N}^{hT/N} a_h\,(\cos\,[\,(\omega_c - n\,p)\,t - \theta\,] + \cos\,[\,(\omega_c + n\,p)\,t - \theta\,]\,)\,dt$$

$$= \frac{1}{T} \sum_{h=1}^{N} a_h \Bigg[ \frac{\sin\,[\,(\omega_c - n\,p)\,h\,T/N - \theta] - \sin\,[\,(\omega_c - n\,p)\,(h-1)\,T/N - \theta]}{\omega_c - n\,p}$$

$$+ \frac{\sin\,[\,(\omega_c + n\,p)\,h\,T/N - \theta] - \sin\,[\,(\omega_c + n\,p)\,(h-1)\,T/N - \theta]}{\omega_c + n\,p} \Bigg]$$

$$= \frac{2}{T} \sum_{h=1}^{N} a_h \Bigg[ \frac{\sin\,(\omega_c - n\,p)\,(T/2N)\cos\,[\,(\omega_c - n\,p)\,(h - 1/2)\,T/N - \theta\,]}{\omega_c - n\,p}$$

$$+ \frac{\sin\,(\omega_c + n\,p)\,(T/2N)\cos\,[\,(\omega_c + n\,p)\,(h - 1/2)\,T/N - \theta\,]}{\omega_c + n\,p} \Bigg]$$

$$= \frac{2 \sin\,(\omega_c - n\,p)\,(T/2\,N)}{T\,(\omega_c - n\,p)} \sum_{h=1}^{N} a_h \cos\,[\,(\omega_c - n\,p)\,(\,h - 1/2\,)\,T/N - \theta\,]$$

$$+ \frac{2 \sin\,(\omega_c + n\,p)\,(T/2\,N)}{T\,(\omega_c + n\,p)} \sum_{h=1}^{N} a_h \cos\,[\,(\omega_c + n\,p)\,(\,h - 1/2\,)\,T/N - \theta\,]\,. \qquad (2)$$

$$\therefore A_n = F'\,(\omega)\,C_n' + F''\,(\omega)\,C_n'', \qquad (3)$$

where: $F'\,(\omega) = \dfrac{2\,N \sin\,(\omega_c - n\,p)\,T/2\,N}{T\,(\omega_c - n\,p)} = \dfrac{4\,s \sin\,(\omega_c - \omega)\,\dfrac{1}{4\,s}}{\omega_c - \omega},$

$$F''(\omega) = \frac{2N \sin(\omega_c + np)\, T/2N}{T(\omega_c + np)}$$

$$= \frac{4\, s \sin(\omega_c + \omega)\, \dfrac{1}{4s}}{\omega_c + \omega},$$

$$C_n' = 1/N \sum_{h=1}^{N} a_h \cos\left[(\omega_c - np)\left(h - \frac{1}{2}\right) T/N - \theta\right],$$

$$C_n'' = 1/N \sum_{h=1}^{N} a_h \cos\left[(\omega_c + np)\left(h - \frac{1}{2}\right) T/N - \theta\right].$$

In a similar manner it can be deduced that

$$B_n = F'(\omega)\, S_n' + F''(\omega)\, S_n'', \tag{4}$$

where:

$$S_n' = -1/N \sum_{h=1}^{N} a_h \sin\left[(\omega_c - np)\left(h - \frac{1}{2}\right) T/N - \theta\right],$$

$$S_n'' = 1/N \sum_{h=1}^{N} a_h \sin\left[(\omega_c + np)\left(h - \frac{1}{2}\right) T/N - \theta\right].$$

Multiplying equation (**4**) by $i$ and subtracting it from (**3**) gives:

$$A_n - i B_n = F'(\omega)\,(C_n' - i S_n') + F''(\omega)\,(C_n'' - i S_n''). \tag{5}$$

It is evident that a special relation exists between $(C_n' - i S_n')$ and $(C_n'' - i S_n'')$ when the carrier frequency is an integral multiple of the dot speed, so that $\omega_c = 2\pi q s$. When $q$ is even, we see by inspection that:

$$C_n' - i S_n' = \frac{e^{-i\left(\frac{\pi q}{2} + \theta\right)}}{N}$$

$$\sum_{h=1}^{N} a_h\, e^{-inp(h-1/2)T/N} = e^{-i\left(\frac{\pi q}{2} + \theta\right)} (C_n - i S_n), \tag{6}$$

where $(C_n - i S_n)$ is the same as for the direct current case. Also:

$$C_n'' - i S_n'' = \frac{e^{-i\left(\frac{\pi q}{2} + \theta\right)}}{N} \sum_{h=1}^{N} a_h\, e^{-inp(h-1/2)T/N}, \tag{7}$$

whence:

$$C_n'' - i S_n'' = e^{i(\pi q + 2\theta)} (C_n' - i S_n') = e^{i2\theta} (C_n' - i S_n')$$
$$= e^{i\left(\frac{\pi q}{2} + \theta\right)} (C_n - i S_n). \tag{8}$$

Substituting (**6**) and (**8**) in (**5**) gives:

$$A_n - i B_n = \left[ e^{-i\left(\frac{\pi q}{2} + \theta\right)} F'(\omega) + e^{i\left(\frac{\pi q}{2} + \theta\right)} F''(\omega) \right] \times (C_n - i S_n). \tag{9}$$

When $q$ is odd, a similar line of reasoning gives:

$$A_n - i B_n = \left[ e^{-i\left(\frac{\pi(q-1)}{2} + \theta\right)} F'(\omega) + e^{i\left(\frac{\pi(q-1)}{2} + \theta\right)} F''(\omega) \right] (C_{N/2-n} + i S_{N/2-n}). \tag{10}$$

$F'(\omega)$ is symmetrical about the carrier frequency in magnitude, but $F''(\omega)$ is unsymmetrical. It will next be shown that $(A_n - i B_n)$ is symmetrical about the carrier frequency when the modulating wave contains no components higher than the carrier frequency. From this it may be inferred that $F''(\omega)$ is zero when these components have been removed from the modulating wave before modulation takes place. For example, let the modulating wave be:

$$\frac{A_0}{2} + \sum_{n=1}^{qN/2} (A_n \cos npt + B_n \sin npt). \tag{11}$$

Multiplying (**11**) by $\cos(\omega_c t - \theta)$ and making use of the trigonometric formulas:

$$\cos a \cos b = (1/2)\cos(a + b) + (1/2)\cos(a - b)$$
$$\cos a \sin b = (1/2)\sin(a + b) - (1/2)\sin(a - b),$$

gives the carrier wave:

$$\frac{A_0}{2}\cos(\omega_c t - \theta) + \frac{1}{2}\sum_{n=1}^{qN/2} \{ [A_n \cos(\omega_c t + npt - \theta) + B_n \sin(\omega_c t + npt - \theta)] + [A_n \cos(\omega_c t - npt - \theta) - B_n \sin(\omega_c t - npt - \theta)] \}. \tag{12}$$

We see by inspection that components of this wave have the same amplitudes, $\sqrt{A_n^2 + B_n^2}$, at equal distances $\pm\, np$ from $\omega$, where $np$ is never greater than $\omega_c$. Hence an analysis of this wave by a method analogous to that given in the earlier part of this appendix, could yield no unsymmetrical shape factor such as $F''(\omega)$.

## Appendix V

*Single Sideband Transmission.* The principle which will be employed in the following discussion is, that when the received wave through any complicated admittance is to be determined, it is permissible to subdivide the admittance into component parts to determine the received wave for each component, and to add the resulting received waves for all the components to obtain the complete wave. To make clear the use of this principle a beginning will be made with the transfer admittance shown at $a$ in Fig. 7. Strictly speaking, this admittance is a hypothetical one only, but it illustrates the principles and is a first approximation to the actual case of band-pass filter.

The admittances are to be taken as real quantities. That is to say, either there is no delay or, if there is any delay, it is equalized and a new time origin is chosen so that the delay disappears from the expression for the admittance. The carrier frequency is assumed to be located at $\omega_c$, and the transfer admittance of the system extends unsymmetrically in the two directions from this frequency as indicated in the figure.

There are infinitely many ways in which this area may be subdivided into component transfer admittances, but the one most suited for our discussion is shown in the remainder of Fig. 7. It will be observed that if the three admittances, (*b*, *c*, and *d*), are added together the result is the admittance shown at *a*. In accordance with the principle set forth above we conclude, therefore, that the received wave, in the case of the admittance shown at *a*, is equal to the sum of the received waves deduced from the other three admittances.

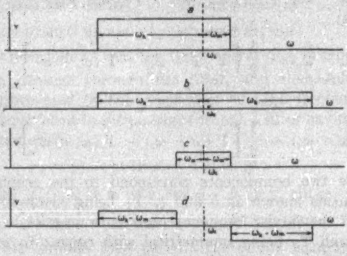

FIG. 7—GRAPHICAL ANALYSIS OF A TRANSMISSION CHARACTERISTIC

**The sum of the transfer admittances shown at *b*, *c*, and *d* equals the transfer admittance shown at *a*. The components, *b*, *c*, and *d*, are chosen so as to possess symmetry about the carrier frequency**

Considering first the admittance shown at *b*, we have here complete symmetry with respect to the carrier frequency; and it follows from the discussion of the symmetrical carrier case that the received wave is of the same frequency and phase as the carrier frequency and is modulated by a low frequency wave, which is identical with that obtained in d-c. telegraphy when a transfer admittance extending from 0 to $\omega_k$ is employed. It is assumed, for simplicity, that the wave used originally to modulate the carrier wave contains no components of as high frequency as the carrier frequency. The discussion of the admittance, shown at *c*, is identical with that of *b*. Comparing these two components, it is concluded that they are in phase relative to each other, and that the component due to *b* builds up more rapidly than that due to *c*. It is obvious that the time it takes the result, due to these two components, to reach a steady state is determined by the slower of the two. We can conclude, tentatively, that, when the carrier frequency is located near one end of the band, it is the frequency range from the carrier frequency to the nearer edge of the transmitted band which determines the rate of building up.

The admittance shown at *d* is also symmetrical about the carrier frequency, but it has a different type of symmetry. To contrast the effect of this kind of symmetry with that of the symmetry previously discussed, let us assume that the carrier wave is represented by cos $\omega_c t$; and that the modulating wave is represented by $A_n$ cos *npt*. The modulated wave is then $A_n$ cos *npt* cos $\omega_c t$. This can be divided in the usual way into two components located symmetrically with respect to the carrier frequency. The two components are

$$(A_n/2) \cos (\omega_c - n\,p)\,t \text{ and } (A_n/2) \cos (\omega_c + n\,p)\,t. \quad \mathbf{(1)}$$

It is obvious that, in the case shown at *b*, these components are transmitted without any relative change and thus combine to form the original modulated wave without any modification other than a possible multiplication by a constant. In the case of the admittance shown at *d*, however, there is a relative change in these components. If one of them is left unchanged, the other is multiplied by − 1 and the two components become

$$(A_n/2) \cos (\omega_c - n\,p)\,t \text{ and } -(A_n/2) \cos (\omega_c + n\,p)\,t. \quad (2)$$

The resultant wave is $A_n$ sin *npt* sin $\omega_c t$. The important change produced by admittances, of the type shown in *d*, is that the carrier frequency has suffered a phase shift of 90 deg. An incidental change is that the modulating frequency, which represents the signal, has also suffered a change of 90 deg. This reasoning can be carried through for all the components making up the modulating wave, as long as their frequency is less than the carrier frequency. It follows that the zeros of the total wave, due to the admittance shown at *d*, are displaced one-quarter period of the carrier wave with respect to the zeros of the corresponding waves obtained with *b* and *c*.

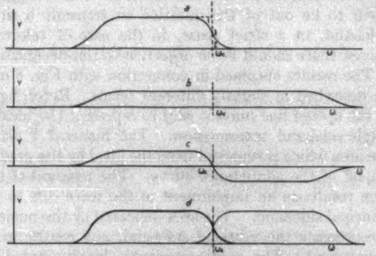

FIG. 8—GRAPHICAL ANALYSIS OF A TRANSMISSION CHARACTERISTIC

**The sum of the symmetrical transfer admittances shown at *b* and *c* equals that shown at *a*. The heavy line in *d* is identical with the curve in *a*; the thin curve is the mirror image of the heavy one. The curve shown at *b* equals one-half the sum, and that shown at *c* equals one-half the difference of the two curves shown at *d***

It will be obvious that if the components due to *c* and *d* could be eliminated, the resultant wave would be determined by the separation between the carrier frequency and the far edge of the band transmitted. The wave, due to admittance shown at *d*, can be eliminated in the reception of the wave by the method discussed under "Phase Discrimination." The wave, due to *c*, is not disposed of so easily. It might be thought that by moving the carrier frequency nearer to the edge of the band the admittance shown at *c* could be made to extend over a very narrow frequency range, and thus be made negligible. It should be noted, however, that the steady state value of the received wave is the same, regardless of the width of the band, and that as long as any portion of *c* remains there will always be a slow, interfering wave. The only satisfactory answer is to locate the carrier frequency exactly on the edge of the band, so that there is no separation, however small, between the edge and the carrier frequency. This peculiar condition is due to the fact that we have assumed a transfer admittance, having an abrupt cut-off.

In the practical case the cut-off is gradual, not abrupt. The transfer admittance shown at *a*, (Fig. 8), represents a transfer admittance (real) which is suitable for single-sideband transmission. It can be separated into two parts as shown, respectively, at *b* and *c*: *c* possesses the kind of symmetry which leads to a phase-quadrature component; and *b* possesses the kind of symmetry which is desirable.

Strictly speaking, it is somewhat inaccurate to apply the term "single sideband transmission" to the case shown in Fig. 8, or, in fact, to any case where portions of both sidebands are transmitted. Since it would seem to be out of the question to transmit a single sideband, in a strict sense, in the case of telegraph waves, there should be no objection to this designation.

The results obtained in connection with Fig. 8 may be described in slightly different terms. Referring to *a*, the dotted line may be said to represent the ideal of single-sideband transmission. The numeral 1 marks the area which is removed from the ideal by the gradual cut-off of the admittance curve. The removal of this area results in an impairment of the wave due to the principal sideband. The area indicated by the numeral 2 represents the vestigial sideband, and results in an impairment. The result obtained, briefly stated is: If areas 1 and 2 are equal, in the sense that when either is rotated through point 3 it can be made to coincide with the other, the impairment due to a missing portion of the principal sideband is exactly compensated for by the wave due to the vestigial sideband.

The discussion above has been limited to the special case of real admittances. In what follows this restriction will be eliminated and general complex admittances will be considered. These do not lend themselves so readily to graphical representation, and for that reason the treatment will be made algebraical instead. There is, however, a close parallelism between the analysis below and that given in Fig. 8, and it is thought that reference to the figure will be useful.

Let the transfer admittance of the given system be denoted by $Y(\omega - \omega_c)$. Consider the admittance represented by $Y(\omega_c - \omega)$. These two characteristics are the mirror images of each other with respect to the carrier frequency. They are illustrated at *d*, in Fig. 8. Next let $Y(\omega - \omega_c)$ be resolved into two components after the manner discussed above

$$Y(\omega - \omega_c) = Y_1(\omega - \omega_c) + Y_2(\omega - \omega_c) \tag{3}$$

where

$$Y_1(\omega - \omega_c) = \frac{1}{2}\Big[Y(\omega - \omega_c) + Y(\omega_c - \omega)\Big] \tag{4}$$

and

$$Y_2(\omega - \omega_c) = \frac{1}{2}\Big[Y(\omega - \omega_c) - Y(\omega_c - \omega)\Big] \tag{5}$$

These two components correspond to the graphical resolution shown at *b* and *c*, $Y_1$ being symmetrical about the carrier frequency both as to magnitude and sign and $Y_2$ being symmetrical with respect to magnitude but reversed with respect to sign.

Let $\cos npt$ be a component of an impressed wave, and let it modulate the carrier wave $\cos \omega_c t$. The resulting wave is

$$\cos npt \cos \omega_c t$$

$$= \frac{1}{2}\cos(\omega_c - np)t + \frac{1}{2}\cos(\omega_c + np)t \tag{6}$$

Consider first the wave resulting from impressing the first of these (the lower sideband) on the admittance $Y_1(\omega - \omega_c)$. Let this admittance be represented by $g_1(\omega - \omega_c) + i\, b_1(\omega - \omega_c)$, the quantities $g_1$ and $b_1$ being real. Impressing the wave $\frac{1}{2}\cos(\omega_c - np)t$ on $g_1$ the resulting wave is

$$\frac{1}{2} g_1(\omega - \omega_c)\cos(\omega_c - np)t$$

or

$$\frac{1}{2} g_1(np)\cos(\omega_c - np)t \tag{7}$$

Similarly, $i\, b_1$ gives rise to the received wave

$$-\frac{1}{2} b_1(np)\sin(\omega_c - np)t \tag{8}$$

Carrying out similar operations for the upper sideband, and remembering the symmetry of $Y_1$, the total wave transmitted by $Y_1$ is

$$\frac{1}{2} g_1(np)[\cos(\omega_c - np)t + \cos(\omega_c + np)t]$$

$$-\frac{1}{2} b_1(np)[\sin(\omega_c - np)t + \sin(\omega_c + np)t] \tag{9}$$

which may also be written

$$g_1(np)\cos npt \cos \omega_c t - b_1(np)\cos npt \sin \omega_c t \tag{10}$$

In a similar manner the wave received through $Y_2(\omega - \omega_c)$ is

$$-g_2(np) \sin npt \sin \omega_c t - b_2(np) \sin npt \cos \omega_c t \quad (11)$$

Now if the wave is demodulated at the receiving end, by multiplying it by the factor $2 \cos(\omega_c t - \phi)$, and if high frequencies are neglected, we have for the received wave after demodulation

$$g_1(np) \cos\phi \cos npt - b_1(np) \sin\phi \cos npt$$

$$- g_2(np) \sin\phi \sin npt - b_2(np) \cos\phi \sin npt \quad (12)$$

It now follows that the three operations, of modulation, passage through the filter, and demodulation supplemented by the suppression of high frequencies, are equivalent to the passage through a filter having the characteristic

$$Y_0(n p) = g_0(n p) + i\, b_0(n p) \quad (13)$$

where $g_0(n p) = g_1(n p) \cos\phi - b_1(n p) \sin\phi$ (14)

$$b_0(n p) = g_2(n p) \sin\phi + b_2(n p) \cos\phi \quad (15)$$

This formula then permits the direct computation of the received wave. It will be noted that $\phi$ may be given an arbitrary value. As a simplifying assumption, we may make $\phi$ equal to the phase shift of the carrier frequency, *i. e.*,

$$\tan\phi = -\frac{b_1(0)}{g_1(0)} \quad (16)$$

## Appendix VI

*Analysis for Generalized Wave Form.* Let it be required to find the sinusoidal components of a periodic telegraph wave whose signal elements have the value:

$$I_h = a_h f(t - (h - 1/2)\, T/N) \quad (1)$$

where $a_h$ is the magnitude factor and

$$f(t - (h - 1/2)\, T/N)$$

is an arbitrary function of time, and may overlap both antecedent and subsequent time units. The origin of $t$ is taken at the beginning of the wave.

The total current, at the time $t$, is:

$$I(t) = \sum_{h=1}^{N} I_h = \sum_{h=1}^{N} a_h f(t - (h - 1/2)\, T/N \quad (2)$$

provided the period $T$ is of greater duration than the wave form.

Let $I(t)$ be represented as a Fourier series; then, by a method similar to that followed in Appendix I

$$A_n = \frac{2}{T} \int_0^T \sum_{h=1}^{N} a_h f(t - (h - 1/2)\; T/N) \cos npt\, dt. \quad (3)$$

Changing the origin of $t$ to the center of the signal element, to which each term in the summation refers, *i. e.*, putting

$$t = (h - 1/2)\, T/N + t'$$

and dropping the prime, we have:

$$A_n = \frac{2}{T} \sum_{h=1}^{N} a_h \int_{-T/2}^{T/2} f(t) \cos\Big(npt + \frac{2\pi n}{N}\Big(h - \frac{1}{2}\Big)\Big)\, dt$$

$$= \frac{2}{T} \int_{-T/2}^{T/2} f(t) \cos npt\, dt \sum_{h=1}^{N} a_h \cos \frac{2\pi n}{N}\Big(h - \frac{1}{2}\Big)$$

$$- \frac{2}{T} \int_{-T/2}^{T/2} f(t) \sin npt\, dt \sum_{h=1}^{N} a_h \sin \frac{2\pi n}{N}\Big(h - \frac{1}{2}\Big)$$

$$= 4s\Big[C_n \int_{-T/2}^{T/2} f(t) \cos npt\, dt - S_n \int_{-T/2}^{T/2} f(t) \sin npt\, dt\Big]. \quad (4)$$

In a similar manner it can be shown that:

$$B_n = 4s\Big[C_n \int_{-T/2}^{T/2} f(t) \sin npt\, dt + S_n \int_{-T/2}^{T/2} f(t) \cos npt\, dt\Big]. \quad (5)$$

Multiplying equation (5) by $i$, and subtracting from (4):

$$A_n - i B_n = F(\omega)\,(C_n - i S_n) \quad (6)$$

Where

$$F(\omega) = 4s \int_{-\infty}^{\infty} f(t)\, e^{-inp}\, dt = 4s \int_{-\infty}^{+\infty} f(t)\, e^{-i\omega t}\, dt. \quad (7)$$

To solve the reverse problem of finding $f(t)$ in terms of $F(\omega)$, put

$$f(t - T/2N) = \frac{A_0}{2} + \sum_{n=1}^{\infty} (A_n \cos npt + B_n \sin npt) \quad (8)$$

which is the Fourier series representing a signal, consisting of a single dot, whose $a_1 = 1$ and other values of $a_h$ are equal to zero.

According to the definitions of $A_n$ and $B_n$ in Appendix I, it is permissible to arrange this expression as follows:

$$f(t - T/2N) = \frac{1}{2} \sum_{n=-\infty}^{\infty} (C_n - i S_n)\, F(\omega)\, e^{i\,npt}. \quad (9)$$

Substituting:

$$C_n = \frac{1}{N} \cos \frac{n\pi}{N} \quad (10)$$

$$S_n = \frac{1}{N} \sin \frac{n\pi}{N} \quad (11)$$

we get

$$f\,(t - T/2\,N) = \frac{1}{2}\sum_{n=-\infty}^{\infty}\frac{F\,(\omega)}{N}\,e^{i\left(npt - \frac{n\,\pi}{N}\right)}\,. \qquad (12)$$

Putting $t = T/2\,N + t'$ and dropping the prime

$$f\,(t) = \frac{1}{2}\sum_{n=-\infty}^{\infty}\frac{F\,(\omega)}{N}\,e^{i\,npt} \qquad (13)$$

As the period approaches infinity, the wave form approaches

$$f\,(t) = \frac{1}{8\,\pi\,s}\int_{-\infty}^{\infty} F\,(\omega)\,e^{i\omega t}\,d\,\omega\,. \qquad (14)$$

Now, in order to observe the effect on the shape factor, let us consider a special wave form, for example, a wave obtained by curbing. For this type of signal the rectangular wave is cut short for a small portion of the time of the value $x$ at the beginning and at the end of each time unit, so that

$f\,(t) = 1$, for $(-\,T/2\,N + x) < t < (T/2\,N - x)$

and

$$f\,(t) = 0$$

for

$-\,T/2\,N < t < (-\,T/2\,N + x)$

and $(T/2\,N - x) < t < T/2\,N$.

For this wave form, equation (**7**) reduces to

$$F\,(\omega) = 4\,s\int_{-T/2N+x}^{T/2N-x}[\cos npt - i\sin npt]\,dt$$

$$= \frac{2\sin\left[\,n\,\pi/N - 2\,\pi\,n\,x/T\,\right]}{n\,\pi/N}\,. \qquad (15)$$

Put $\qquad x = T/8\,N,$

which corresponds to a shortening of the time during which the battery is applied to the cable to ¾ of the length of the total time unit, and apply ground during the remaining portion. For this case

$$F\,(\omega) = \frac{8\,s\sin\,(3\,\omega/16\,s)}{\omega}\,. \qquad (16)$$

Comparing this shape factor with the corresponding one for the non-curbed wave, (given in Appendix I), equation (**6**), it is seen that the effect of curbing is to multiply the shape factor by $\sin\dfrac{3}{16}\dfrac{\omega}{s}\Big/\sin\dfrac{\omega}{4\,s}$. A network having this characteristic in the transmitted range would be equivalent to the curbing.

## Appendix VII

*Distortion Correction by Signal Shaping.* The problem is: Given an arbitrary transfer admittance, *i. e.*, one which is not ideal, how should the sent wave be shaped in order that the received wave may be non-distorting? It is proposed to derive the solution for the case, where the value of the received wave at the middle of the time unit is taken as criterion for distortionless transmission. There are many solutions to this problem, and we will restrict ourselves, at the outset, to a particular type of wave form for the signal elements of the sent wave; namely, the type wherein each signal element is made up of a series of rectangular steps, each of one time unit duration (Fig. 9). The problem, then, consists in finding the height of each step.

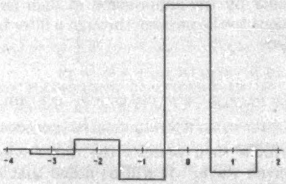

FIG 9—EXAMPLE OF SIGNAL SHAPING TO PRODUCE DISTORTIONLESS RECEIVED SIGNALS

By changing the point of view somewhat, it is possible to make use of some previously obtained results. Let us temporarily look on the unknown signal element, not as a signal element but as a signal made up of a succession of rectangular elements. The wave form of the unknown signal element is $f_s\,(t)$, and the magnitude factors of the individual rectangular elements are the unknown quantities $b_1,\ b_2,\ \ldots\ b_N$. We have

$$f_s\,(t) = \frac{A_0}{2} + \sum_{n=1}^{\infty}(A_n\cos npt + B_n\sin npt)\,. \qquad (1)$$

The shape factor of the rectangular signal element is

$$\frac{8\sin\,\omega/4\,s}{\omega/s}$$

and the discrimination factor obtained by looking at the sought signal element, as a signal, may be taken to be $(C_n - i\,S_n)$. The problem is now reduced to finding $C_n$ and $S_n$ for all values of $n$ from 0 to $N/2$, since with these values known the $b$'s are determined uniquely. Equation (**1**) may be arranged as follows:

$$f_s\,(t) = 4\,s\sum_{n=-\infty}^{\infty}(C_n - i\,S_n)\,\frac{\sin\,\omega/4\,s}{\omega}\,e^{inpt} \qquad (2)$$

The transfer admittance of any network may be represented by $Y\,(\omega)$. In order to be more general, multiply $Y\,(\omega)$ by $e^{-i\omega\tau}$; where $\tau$ is an arbitrary constant, and is of the nature of a constant delay. Let $Y\,(-\,\omega) = \overline{Y}\,(\omega)$, where the bar denotes the conjugate of $Y\,(\omega)$.

The wave received over a circuit having this transfer admittance is:

$$f_r(t) = 4s \sum_{n=-\infty}^{\infty} (C_n - i S_n) \frac{\sin \omega/4s}{\omega} Y(\omega)\, e^{-i\omega\tau}\, e^{inpt} \tag{3}$$

Let
$$H(\omega) = \frac{\sin \omega/4s}{\omega} Y(\omega)\, e^{-i\omega\tau} \tag{4}$$

and rearrange terms

$$f_r(t) = 4s \sum_{n=-N/2}^{(N/2)-1} \sum_{q=-\infty}^{\infty} (C_{qN+n} - i S_{qN+n}) \times H(4\pi s[q + n/N])\, e^{i(qN+n)pt} \tag{5}$$

It may be deduced from equations (**7**) and (**8**) of Appendix I, that

$$C_{qN+n} - i S_{qN+n} = (-1)^q (C_n - i S_n) \tag{6}$$

The receiving mechanism has been assumed to respond to the ordinate of the received wave at the middle of each time unit, (as representative of the signal for that unit), at which time

$$pt = \frac{\pi}{N}(2h - 1) \tag{7}$$

where $h$ has values 1, 2, 3 . . . $N$ for successive time units. We note that

$$e^{i(qN+n)pt} = e^{i(qN+n)(2h-1)\pi/N} = (-1)^q e^{i2\pi n(h-1/2)/N}. \tag{8}$$

Substituting equations (**6**) and (**8**), in (**5**), gives:

$$f_r(t) = 4s \sum_{n=-N/2}^{(N/2)-1} (C_n - i S_n)\, e_i^{2\pi n(h-1/2)/N} \sum_{q=-\infty}^{\infty} H(4\pi s[q + n/N]) \tag{9}$$

at the middle of the time units.

If we put $f_r(t) = 1$ for $h = 1$, and $f_r(t) = 0$ for $h = 2, 3$, etc., then the received wave has the effect of a single dot standing by itself.

Our next step is to solve the $N$ equations, such as (**9**), for the $N$ unknown values of $(C_n - i S_n)$, in order that we may be able to use the results in computing the sent wave. In a manner similar to that in Appendix II, multiply each of the simultaneous equations by $\cos \frac{2\pi k}{N}(h - 1/2)$, and add all the equations:

$$\cos \pi k/N = 2s \sum_{n=-N/2}^{(N/2)-1} (C_n - i S_n) \times \left( \frac{\cos(n+k)\pi \sin(n+k)\pi}{\sin(n+k)\pi/N} + \frac{\cos(k-n)\pi \sin(k-n)\pi}{\sin(k-n)\pi/N} + i \frac{\sin^2(n+k)\pi}{\sin(n+k)\pi/N} - i \frac{\sin^2(k-n)\pi}{\sin(k-n)\pi/N} \right) \sum_{q=-\infty}^{\infty} H(4\pi s[q + n/N]) \tag{10}$$

as $k$ approaches any integral value, $m$, from $-N/2$ to $N/2$ inclusive, the numerators in the middle factor of each of the terms of the summation of equation (**10**) approach zero. Consequently, the factors are zero excepting one whose $n = +m$ and one whose $n = -m$, wherein certain denominators also approach zero, with the result that equation (**10**) reduces to

$$\cos \pi m/N = 2Ns(C_m - i S_m) \sum_{q=-\infty}^{\infty} H(4\pi s[q + n/N]) + 2Ns(C_{-m} - i S_{-m}) \sum_{q=-\infty}^{\infty} H(4\pi s[q - n/N]). \tag{11}$$

When each of the $N$ equations such as (**9**) is multiplied by $\sin \frac{2\pi k}{N}\left(h - \frac{1}{2}\right)$, a similar line of reasoning gives

$$\sin \pi m/N = i2Ns(C_m - i S_m) \sum_{q=-\infty}^{\infty} H(4\pi s[q + n/N]) - i2Ns(C_{-m} - i S_{-m}) \sum_{q=-\infty}^{\infty} H(4\pi s[q - n/N]) \tag{12}$$

Multiplying (**12**) by $i$, subtracting from (**11**), and putting $m = n$ gives

$$\cos \pi n/N - i \sin \pi n/N = 4Ns(C_n - i S_n) \sum_{q=-\infty}^{\infty} H(4\pi s[q + n/N]) \tag{13}$$

$$\therefore C_n - i S_n = \frac{e^{-in\pi/N}}{4Ns \sum_{q=-\infty}^{\infty} H(4\pi s[q + n/N])} \tag{14}$$

At the sending end, the height of the $h$th step, for any convenient value of $t$ during that time interval, is given by formula (**2**). Where the steps are rectangular, it is more convenient to use the formula

$$b_h = C_0 + \text{real part of } 2 \sum_{n=1}^{N\,2-1} (C_n - i S_n)\, e^{i\frac{2\pi n}{N}(h-1/2)}$$

$$+ S_{N/2} \sin \pi (h - 1/2) \,. \qquad \textbf{(15)}$$

Substituting from (**14**) and (**4**):

$$b_h = \frac{1}{N} \left( \frac{1}{Y(0)} + \text{real part of} \right.$$

$$\left[ 2 \sum_{n=1}^{N/2-1} \frac{e^{i\frac{2\pi n}{N}(h-1+2s\tau)}}{\sin \dfrac{\pi n}{N} \displaystyle\sum_{q=-\infty}^{+\infty} \frac{Y(4\pi s[q + n/N])}{\pi [q + n/N]} \; e^{-i(4s\tau+1)q\pi}} \right.$$

$$\left. \left. + \frac{e^{i\pi(h-1+2s\tau)}}{\displaystyle\sum_{q=-\infty}^{+\infty} \frac{Y(4\pi s[q + 1/2])}{4\pi s[q + 1/2]} \; e^{-i(4s\tau+1)q\pi}} \right] \right) \qquad \textbf{(16)}$$

In using formula (**16**) for computing $b_h$, it will be understood that $Y$ and $s$ are the given quantities of the problem. The quantities $N$ and $\tau$ which occur in addition to $Y$ and $s$ require comment. In the first place, $\tau$ is an arbitrary quantity and may be given, for instance, the value zero. By giving it, in succession, all the values between zero and $1/2\,s$ an infinite number of distinct solutions are obtained. The solution which is preferable, from a practical standpoint, may be selected after computations are completed for a number of values of $\tau$. As for $N$, it should be chosen large in proportion to the precision required. It should be an even number, and preferably not less than twice the number of steps to be used.

The sum which occurs in the denominator is an infinite series, but it converges rapidly and in most practical cases it should be sufficient to use three or four terms. The function $Y$ occurs with negative arguments in this expression. This does not imply negative frequencies but is merely to be taken as a convenient notation. The expression $Y(-\omega)$ is merely to be interpreted as the conjugate of $Y(\omega)$ where $\omega$ is positive.

## Appendix VIII

It is required to compute the mean power of a wave characterized by the shape factor,

$$F(\omega) = 2, \text{ for } 0 < \omega < 2\pi s,$$
$$F(\omega) = \sqrt{2}, \text{ for } \omega = 2\pi s,$$
$$F(\omega) = 0, \text{ for } \omega > 2\pi s.$$

Such a wave is

$$A_0/2 + \sum_{n=1}^{N/2} (A_n \cos npt + B_n \sin npt) \,. \qquad \textbf{(1)}$$

It will be sufficient to add the squares of the sinusoidal amplitudes divided by 2, to the square of the d-c. component. This gives for the mean power

$$A^2{}_0/4 + \left( \sum_{n=1}^{N/2-1} (A^2{}_n + B^2{}_n)/2 \right) + \frac{B_{N/2}{}^2}{2} \,. \qquad \textbf{(2)}$$

Since

$$A_n = 2\,C_n, \qquad \text{for } n < N/2,$$
$$B_n = 2\,S_n, \qquad \text{for } n < N/2,$$
$$B_{N/2} = \sqrt{2}\,S_{N/2},$$

the power is:

$$C^2{}_0 + 2 \sum_{n=1}^{(N/2)-1} (C^2{}_n + S^2{}_n) + S^2{}_{N/2} \,. \qquad \textbf{(3)}$$

Now

$$C_n{}^2 = \frac{1}{N^2} \sum_{h=1}^{N} \sum_{q=1}^{N} a_h\, a_q \cos \frac{2\pi n}{N} \times$$

$$(h - 1/2) \cos \frac{2\pi n}{N} (q - 1/2) \,, \qquad \textbf{(4)}$$

$$S^2{}_n = \frac{1}{N^2} \sum_{h=1}^{N} \sum_{q=1}^{N} a_h\, a_q \sin \frac{2\pi n}{N}$$

$$(h - 1/2) \sin \frac{2\pi n}{N} (q - 1/2) \,. \qquad \textbf{(5)}$$

Adding

$$C^2{}_n + S^2{}_n = \frac{1}{N^2} \sum_{h=1}^{N} \sum_{q=1}^{N} a_h\, a_q \cos \frac{2\pi n}{N} (h - q) \,. \qquad \textbf{(6)}$$

Substituting equation (**6**) in (**3**) and remembering that $C_{N/2}$ and $S_0$ are identically equal to zero, the total power becomes:

$$\frac{1}{N^2} \sum_{h=1}^{N} \sum_{q=1}^{N} a_h\, a_q \left( 1 + 2 \sum_{n=1}^{(N/2)-1} \cos \frac{2\pi n}{N} (h - q) \right.$$

$$\left. + \cos \pi (h - q) \right)$$

$$= \frac{1}{N^2} \sum_{h=1}^{N} \sum_{q=1}^{N} a_h\, a_q \left[ \sum_{n=0}^{(N/2)-1} \cos \frac{2\pi n}{N} (h - a) \right.$$

$$\left. + \sum_{n=1}^{N/2} \cos \frac{2\pi n}{N} (h - q) \right]$$

$$= \frac{1}{N^2} \sum_{h=1}^{N} \sum_{q=1}^{N} a_h\, a_q \left( \frac{\cos \dfrac{\pi}{N} (h-q) \sin \pi (h-q)}{\sin \pi (h - q)/N} \right). \qquad \textbf{(7)}$$

The expression in parenthesis is equal to zero unless $h = q$, in which case it equals $N$. Hence the power is:

$$\frac{1}{N}\sum_{h=1}^{N} a_n^2 . \tag{8}$$

## Appendix IX

*The Fourier Integral.* Up to the present the Fourier series theorem has been used in the analysis to the exclusion of the Fourier integral theorem which is closely related to it, and it seems desirable to give a brief discussion of the Fourier integral at this point. In order to keep the discussion brief it will be necessary to make it sketchy and incomplete in respect to details. The complex notation will be used because of its compactness.

The Fourier integral theorem states that

$$f(t) = \frac{1}{\pi}\int_{0}^{\infty} du \int_{-\infty}^{+\infty} f(\lambda)\cos u\,(t-\lambda)\,d\,\lambda, \tag{1}$$

regardless of the form of the function $f(t)$, provided it meets certain requirements. The requirement which is of importance in telegraph theory is that

$$\int_{-\infty}^{+\infty} |\,f(t)\,|\,dt = \text{a finite number.} \tag{2}$$

The quantity $u$ is so far a mathematical quantity which serves only as a variable under the integral sign, in the same sense that $\lambda$ does. In studying the integrand it will be assumed that $u$ is identical with the quantity $\omega$ which occurs in expressions for impedances and admittances. With this assumption the theorem expressed by equation (**1**) can be written, in complex notation:

$$I(t) = \frac{1}{2}\int_{-\infty}^{+\infty} J(\omega)\,e^{i\omega t}\,d\,\omega, \tag{3}$$

$$J(\omega) = \frac{1}{\pi}\int_{-\infty}^{+\infty} I(t)\,e^{-i\omega t}\,dt. \tag{4}$$

$I(t)$ expresses the wave as a function of time and $J(\omega)$ expresses it as a spectrum or a function of frequency.

For comparison we will now write down the Fourier series theorem in an analogous form:

$$I(t) = \frac{1}{2}\sum_{-\infty}^{+\infty} K(\omega)\,e^{i\omega t}\,\Delta\,\omega, \tag{5}$$

$$K(\omega) = \frac{1}{\pi}\int_{-\pi/\Delta\omega}^{+\pi/\Delta\omega} I(t)\,e^{-i\omega t}\,dt\,. \tag{6}$$

where $\omega$ takes the values 0, $\pm\,\Delta\,\omega$, $\pm\,2\,\Delta\,\omega$, etc., and $\Delta\,\omega$ is $2\,\pi$ times the reciprocal of the fundamental period of the series. It will be apparent that there is a close, formal similarity between equations (**3**) and (**4**) on the one hand, and equations (**5**) and (**6**) on the other.

Now let the wave $I(t)$ represent an arbitrary telegraph signal made up of $N$ signal elements. Formulas (**4**) and (**6**) give alternative ways for expressing the wave spectrally. The latter represents the wave as a series of discrete frequency components; the former represents it as a continuous spectrum. Both representations are exact when properly interpreted, although they differ in form; for when substituted in formulas (**5**) and (**3**) respectively they yield the original wave precisely. Both representations are limited to a finite number of signal elements,—the series because its period must be finite, and the integral because of equation (**2**).

While these analyses are true for any succession of $N$ signal elements which may be selected, their utility depends upon severe restrictions on the signal elements which precede and follow the signal under analysis. To be of value in circuit theory the series demands that the succeeding and preceding elements consist of an indefinitely great number of repetitions of the signal under analysis. Similarly, the integral depends for its utility on the assumption that it is followed and succeeded by infinite sequences of elements having the magnitude zero. These restrictions are normally not serious because there is no limitation on $N$ other than that it should be finite. In addition to being equally exact, the two methods then appear to be substantially equally general (or restricted) in respect to the complexity of telegraph signals which they are capable of representing.

As might be surmised, most of the results obtained in the paper follow from either method of treatment. First, if the d-c. wave is analyzed by the integral method it will be found that $J(\omega)$ separates into two factors, a discrimination factor and a shape factor. The discrimination factor has the property of falling into equivalent bands, each of width equal to the speed of signaling. From this it is concluded that the necessary frequency range does not exceed the speed of signaling. The various ideal form factors corresponding to various criteria follow with somewhat greater difficulty. Whereas the series treatment led to a system of linear algebraic solutions, the integral treatment leads to a system of integral equations.

The only outstanding difficulty with the integral analysis appears in connection with establishing the fact that the minimum frequency band equals the speed of signaling. In other words, while it is easy to show that the information contained in one frequency band of width $(s)$ is sufficient for the transmission of intelligence, it is difficult to show that it is also necessary. On the series analysis as used in the paper, this result followed very easily from the well-known principle that the number of unknowns which can be found does not exceed the number of given equations. When the frequency components are not discrete but form a continuous spectrum no such simple argument appears to be available. A somewhat full discussion will be given.

On considering the matter it is apparent that the difficulty arises from the lack of a precise formulation of what is meant by transmitting intelligence. No formal criterion was necessary in the case of the Fourier series treatment, but it will be necessary to formulate one to make satisfactory progress with the integral treatment. Stated in general terms the requirement of the received wave is that it should be possible to make measurements on it extending over a finite interval, and from these measurements (together with the known properties of the admittance) to determine the sent wave. More specifically, it should be possible to express the magnitude factors of the sent wave as a linear sum (or integral) of the measured values of the received wave. If the sent and received waves are expressed as functions of $\omega$, and the computations modified accordingly, it is obvious that the operations can be carried out on the sent wave in which case the received wave will be non-distorting. We may then lay down as a criterion for a telegraph system's ability to transmit intelligence, that it should be possible to shape the sent signals so as to make the received wave non-distorting. In the remainder of the appendix this criterion will be used. It will be apparent that the introduction of this criterion constitutes, in a sense, a fresh start.

Taking for the criterion of a non-distorting wave that it should have correct magnitude at the central point of the time unit, and limiting the discussion to the case where the frequency is limited to the range $0 - s$, the shape factor of the received wave is uniquely determined and is 2 throughout that range. The shape factor of the transmitted wave is $2/Y$ and the wave form at the sending end is

$$f_s(t) = \int_{-2\pi s}^{+2\pi s} \frac{2\, e^{i\omega t}\, d\,\omega}{Y(\omega)}. \qquad (7)$$

If $1/Y$ is finite throughout this range, this integral has a definite value. If $Y$ has a simple zero at $\omega = \omega_a$ the integral may be written

$$f_s(t) = e^{i\omega a t} \int_{-2\pi s}^{+2\pi s} \frac{2\, e^{i(\omega - \omega a)t}\, d\,\omega}{Y(\omega)}. \qquad (8)$$

The first derivative with respect to $t$ of the definite integral may now be evaluated. The derivative is determinate and by integrating it with respect to $t$ a suitable value for $f(t)$ may be obtained.

If $Y$ has a finite number of simple zeros, the function $1/Y$ may be broken up into a number of terms each of which has not more than one simple zero; and the individual terms can be treated as above.

When the function $Y$ has double zeros, or zeros of any finite order of multiplicity, suitable values of the function $f(t)$ can be found by an extension of the same method.

The significant results for a simple case will now be stated. Suppose that the transfer admittance has a simple zero at the origin (as in telegraphing through a transformer); the sent wave, which gives a distortionless received wave, does not approach zero as $t$ approaches $+\infty$ but approaches a constant $a$. If the zero at the origin is double (telegraphing through a high-pass filter, made up of one series condenser and one shunted coil) the sent wave should approach the value $b\,t$ as $t$ approaches $\infty$. For a triple zero the corresponding asymptotic value is of the form $c\,t^2$, etc. It is obvious that as the multiplicity of the zero increases the function representing the sent wave rapidly becomes more and more unmanageable. Now, if $Y$ becomes zero throughout a finite interval at the origin, we may think of it as having a zero of an infinite order of multiplicity. It is to be expected then that there should be no finite function capable of satisfying the requirements.

# Automatic Control of Edison Systems

## As Applied in the St. Charles Street Substation of the Union Electric Light and Power Company

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Associate, A. I. E. E. Associate, A. I. E. E.

*Synopsis.—A brief description of the Edison System at St. Louis is given, and power supply, service restoration, and system balance are discussed. The history of the application of automatic control equipment to the system and a brief résumé of operating experiences are also given.*

*The relation of the St. Charles St. Substation to the remainder of the system is pointed out and certain features of its design explained. The scheme of loading the machines and the method of load shifting between machines is given in detail, and a table is given to show the "set-up" for any load. The distinctive features of the various types of machines at this station are discussed, particular attention being given to the control of the converter with transformer taps and high-voltage revolving field booster. The scheme of automatically changing taps under load is described fully. A brief summary of the protective features on this machine is also given.*

*The operating experience with the automatic equipment at the St. Charles St. Station is related.*

* * * * *

### INTRODUCTION

EDISON d-c. systems in large cities have been the result of natural growth and in many cases have reached such a size that their replacement would be a tremendous undertaking even though a careful study might indicate that such a step might be desirable from an engineering standpoint. Since the operation of Edison systems is a big problem to many companies, it was felt that a description of the manner of revamping the Edison system in St. Louis and the results obtained would be of interest. In revamping this system the use of automatically controlled machines was thoroughly studied and tried out. In this paper particular emphasis is given to the application of automatic control to the St. Charles Street Substation, Fig. 1, which is the largest Edison station and represents the latest design of equipments.

### THE EDISON SYSTEM

The 250-volt Edison district of the Union Electric Light and Power Company covers an area approximately one mile wide by 1¾ mi. long and at present attains a peak load of approximately 32,000 kw. The district is supplied from eight substations located as shown on Fig. 2.

The a-c. power supply to the stations is derived from two separate and distinct systems, the system supplying each station being given in Table I. Five of the stations are supplied at 60 cycles and three at 25 cycles with approximately 50 per cent of the total capacity at each frequency. The 25-cycle power is generated at the Keokuk hydroelectric plant and at the Ashley St. steam plant. The 60-cycle power is supplied by the Cahokia and Ashley St. steam plants. In other words, the Edison stations receive power at two frequencies and from two plants at each frequency, so that trouble on either system or at any plant will only partly affect the Edison load.

No stand-by batteries are maintained on the 250-volt Edison system, the last ones having been disconnected from the system about four years ago. Although this type of load demands a high degree of service continuity, it was felt that the improved reliability of the a-c. supply, together with the use of automatic control equipment for service restoration, made the batteries unnecessary. Motor-generator sets are relied upon for service restoration, all of them having stable operation at all voltages and all are a-c., starting with the exception of two of the manual motor-generators at Twentieth Street. The rotary-converters are capable of operation through a considerable range of d-c. voltage and all are a-c. starting. The three 9000-ampere, 60-cycle converters have a lower limit at 50 per cent voltage while the others have lower limits varying from 60 to 90 per cent.

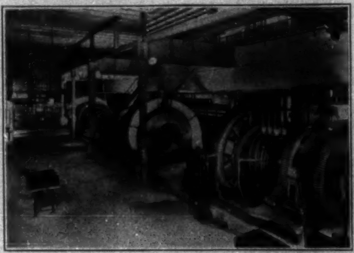

FIG. 1—GENERAL VIEW OF ST. CHARLES ST. STATION INTERIOR

It will be noted from Table I, that somewhat in excess of 50 per cent of the capacity is in motor-generators. This means that in the event of a complete Edison system outage, the motor-generators will "come in" first and will be of sufficient capacity to raise the voltage

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to something above 50 per cent. At this point the first converters will "come in" and further raise the voltage, being followed by the other converters as the system reaches their lower operating limit. As added insurance that the motor-generators will produce enough voltage for the converters to "come in," should some machines be out of service, most of the motor-generators have an emergency capacity of 120 per cent load for a limited period during times of low voltage.

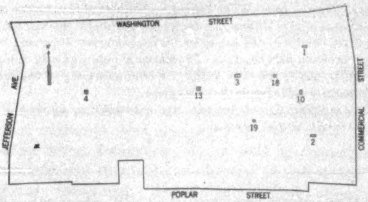

FIG. 2—OUTLINE OF ST. LOUIS EDISON DISTRICT SHOWING LOCATION OF SUBSTATIONS

This district is about 1¾ by 1 mi. in area.

TABLE I
SUBSTATION DATA

| Substation | | Supply frequency | Control | Apparatus | | | | Station total capacity d-c. amperes | Station load at time of system peak 12-22-26 d-c. amperes |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Motor-gen. | | Converter | | | |
| Name | No. | | | No. | Capacity d-c. amperes | No. | Capacity d-c. amperes | | |
| Lucas Ave. | 1 | 60 | Auto. | 1 | 7,500 | 1 | 9,000 | 16,500 | 16,400 |
| Walnut St. | 2 | 60 | Auto. | 1 | 7,200 | 1 | 9,000 | 16,200 | 16,200 |
| Twelfth Blvd. | 13 | 60 | Auto. | 1 | 7,200 | .. | | 7,200 | 6,800 |
| Railway Exchange | 18 | 60 | Auto. | 1 | 15,000 | .. | | 15,000 | 14,800 |
| Eighth St. | 19 | 60 | Auto. | 1 | 7,500 | 1 | 9,000 | 16,500 | 14,700 |
| Total 60 cycle | | | | | 44,400 | | 27,000 | 71,400 | 68,900 |
| St. Charles St. | 3 | 25 | Auto. | 2 | 14,400 | 2 | 16,400 | 30,800 | 30,100 |
| Twentieth St. | 4 | 25 | Auto. | 1 | 7,200 | .. | | 28,200 | 22,700 |
| | | | Man. | 3 | 12,000 | 1 | 9,000 | | |
| Boatmen's Bank | 10 | 25 | Man. | .. | | 2 | 16,000 | 16,000 | 7,500 |
| Total 25 cycle | | | | | 33,600 | | 41,400 | 75,000 | 60,300 |
| Total Edison System | | | | | 78,000 | | 68,400 | 146,400 | 129,200 |

NOTE. All current values at 250 volts.

The system neutral is supplied by the rotary converters, the motor-generators being two-wire machines in every case. The converters are fairly well distributed over the system and a sufficient number are kept running during the night to properly maintain the neutral. However, to protect against destructive voltages on one side of the system, due possibly to a shortage of three-wire machines at times of trouble, the motor-generators are provided with relays to prevent more than 55 per cent of normal voltage between either side of the system and neutral. In other words, the control is arranged so that with the system unbalanced, the voltage between the highest side and the neutral will not greatly exceed one-half of the normal maximum across it, the total voltage being whatever it may.

### AUTOMATIC DEVELOPMENT

The company's first automatically operated d-c. machine was installed in 1922 at the Twelfth Boulevard Substation. The automatic features were considered somewhat of an experiment by the operating engineers but their installation was felt to be justified as the station was very close, electrically, to the St. Charles Street Substation and as it was located in the basement of the company's office building, it was possible to give it close observation.

Many difficulties were encountered in putting the equipment into service initially, but they were principally unforeseen operating problems or troubles with individual devices and not faults of the fundamental scheme of control. In practically every case, these difficulties were remedied by making certain alterations or additions either to details of the general scheme or to some particular device. During several system disturbances, the automatic control gave a good account of itself and functioned exactly as intended. It was apparent that automatic control was a practical thing and well worth further application.

In 1923 another 1800 kw. motor-generator, automatically operated, was purchased and installed at the Walnut St. Station. This station was then manually operated and the automatic machine was intended to relieve the off peak shift of operators, as well as to replace certain depreciated machines.

The scheme of control was somewhat different from the Twelfth Boulevard Station and included some previously untried device applications. Again many difficulties arose but in most cases the remedies were comparatively simple. It was felt that cooperation between the manufacturer and the operating company had solved many problems and that further experience and cooperation would result in additional improvements.

The third installation was made in 1924 and was a 3750-kw. motor-generator set installed in the very heart of the Edison load at a new station known as the Railway Exchange Substation. This was a three-unit set, one motor driving two generators in parallel with provisions for balancing the load on the generators. At that time it was reputed to be the largest automatically-controlled motor-generator set in Edison service.

At this time almost every case of trouble had its lesson, for it usually indicated a weak point in a particular scheme or device or a peculiar operating condition which had not been foreseen. A case of trouble on one automatic equipment usually meant the possibility of the same thing occurring on the others and consequently the remedy had to be applied to all.

The next addition was at the Eighth Street Substation. This was a new station in which was installed a 2250-kw. rotary converter and an 1875-kw. motor-generator set operating in parallel on both the a-c. and d-c. sides. The scheme of automatically operating machines of these characteristics in parallel was entirely new and several problems arose on that account.

Immediately after the Eighth Street installation was made, a duplicate 2250-kw. converter was installed at the Walnut St. Substation and interlocked so as to operate in parallel with the motor generator set installed there in 1923. This released all operators from Walnut St. and made the station fully automatic.

By the middle of 1925 all of the machines had had opportunities to perform on service restoration under various conditions. On almost every occasion they functioned properly and were carrying the load before the manual stations. Although troubles were still occurring, they were generally of a minor nature and most of them were being detected during regular inspections and before damage resulted. It was felt that the practicability of automatically controlled machines on a large system had been definitely proved.

## THE ST. CHARLES STREET SUBSTATION

The St. Charles Street Substation has always been the largest Edison station and being very close to the load center, it has always been considered a base load station. Its d-c. feeders interlace with those of five other stations and it can affect more of the system than any other station. In 1925 all of the manual machines at St. Charles Street were, with one exception, reaching the end of their life and it was necessary that they be replaced. There was no question of whether the new machines should be manually or automatically controlled for aside from the apparent saving in operating expenses, the experience with automatic substations had demonstrated their ability to withstand system disturbances, their greater speed in service restoration, and their superior voltage regulation.

In planning the station it was found that no additional load was to be provided for at this time, the station capacity remaining at approximately 7500 kw. In accordance with the practise of having half the capacity in motor generators and half in converters, there were to be installed about 3750 kw. in each type of machine. Two 1800-kw. motor-generators were decided upon, as they matched the sizes of others in service and were standard with the manufacturers. It was felt that the condition of the 2000-kw. booster converter already in the station, although 8 years old, warranted the expense of automatic control. This left about 1900 kw. for new converter capacity. A 2250-kw. converter was selected, it being a standard size and of the same capacity as others in service.

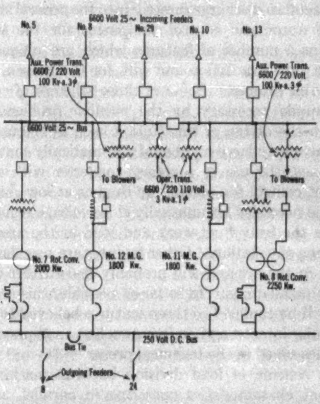
6600 Volt 25~ Incoming Feeders
No. 5
No. 8
No. 29
No. 10
No. 13
Aux. Power Trans. 6600 / 220 Volt 100 Kv-a. 3 φ
Aux. Power Trans. 6600 / 220 Volt 100 Kv-a. 3 φ
6600 Volt 25~ Bus
To Blowers
Oper. Trans. 6600 / 220 110 Volt 3 Kv-a. 1 φ
To Blowers
No. 7 Rot. Conv. 2000 Kw.
No. 12 M. G. 1800 Kw.
No. 11 M. G. 1800 Kw.
No. 8 Rot. Conv. 2250 Kw.
Bus Tie
250 Volt D. C. Bus
Outgoing Feeders
8
24

FIG. 3—ONE-LINE DIAGRAM OF ST. CHARLES ST. SUBSTATION

Fig. 3 shows a one-line diagram of the station. It will be noted that power is received at 6600 volts, 25 cycles, over five underground feeders. The a-c. structure is insulated for 13,200 volts and all machines are provided for reconnection to that voltage, in order that the station can be changed over to the higher voltage at some future time with a minimum amount of work. The outgoing feeders are of 1,500,000 cm. and 2,000,000 cm. cross-section, about one-third being of the larger size.

The ventilating equipment is probably of interest There are two blowers, each rated at 57,000 cu. ft. per min. at 3½ in. pressure and driven by 50-hp. a-c motors. One blower is "preferred" and runs when ever any machine is running while the second "comes on" when the general station air or the discharge air reach certain predetermined temperatures. A throw-over switch is provided to make either blower "preferred," the other operating on temperature.

The flow of air through the station is opposite to natural circulation. The air enters the station from a shaft through the roof and is drawn into the machines which have their end bells left off. The machines discharge into the basement beneath them from which point the blowers draw the air to discharge it through a stack in a corner of the station. This results in the general station being in the "intake" and at a slight vacuum so that any leakage around doors or windows will let cool air enter the station rather than cause air to be wasted, as is the case in systems where the general station is under pressure. This also results in more bearable summer temperatures than in systems where the machines discharge directly into the general station.

The automatic control equipment for the station contains a number of features which are unique and new in this installation and will, for this reason, be of particular interest. Some of these schemes of control were made necessary by the peculiar problems met with in the design of this station such as the use of a comparatively large number of automatically controlled machines, the use of a rotary converter with a new type of control for picking up the bus at low voltages, and the necessity for unusually close voltage regulation due to the heavy net-work and load in the area surrounding the station. Other features are new developments in the art and will probably find further use in other installations. In so far as possible, this description will be confined to those features believed to be of particular interest and omitting such as have previously been described in the technical press.

The scheme of load division between machines of different characteristics operating in parallel, as employed at this station, was conceived and originally applied at the Eighth Street Substation by the company's operating engineers. The application in this case was simply an extension of the original scheme.

### STARTING, STOPPING AND LOADING SEQUENCE

The entire sequence of operations with operating values is outlined in Table II. During normal light-load conditions the tap changing booster-type rotary converter, machine No. 8, supplies the entire station load. The station voltage is regulated by variation of the motor-operated booster field rheostat in response to the voltage regulating relay No. 58. This voltage regulating relay is controlled by potential from a pressure wire bus so that it tends to hold the net-work potential constant within its area. The bus voltage therefore varies in accordance with load conditions.

TABLE II
LOADING SEQUENCE CHART

| Load on machine | | | | Total load on station | Operating condition |
|---|---|---|---|---|---|
| No. 8 | No. 12 | No. 11 | No. 7 | | |
| 1000 | 0 | 0 | 0 | 1,000 | Minimum load |
| | | | | | Load increases |
| 8400 | 0 | 0 | 0 | 8,400 | No. 8 gives signal to start No. 12 |
| 7000 | 1400 | 0 | 0 | 8,400 | After No. 12 is on |
| | | | | | Load increases |
| 7000 | 6300 | 0 | 0 | 13,300 | Before No. 12 recalibrates No. 8 |
| 9000 | 4300 | 0 | 0 | 13,300 | After No. 12 recalibrates No. 8 |
| 9000 | 6800 | 0 | 0 | 15,800 | No. 12 gives signal to start No. 11 |
| 9000 | 5200 | 1600 | 0 | 15,800 | After No. 11 is on |
| | | | | | Load increases |
| 9000 | 5200 | 6300 | 0 | 20,500 | Before No. 11 recalibrates No. 12 |
| 9000 | 7200 | 4300 | 0 | 20,500 | After No. 11 recalibrates No. 12 |
| | | | | | Load increases |
| 9000 | 7200 | 6800 | 0 | 23,000 | No. 11 gives signal to start No. 7 |
| 9000 | 5200 | 1400 | 7400 | 23,000 | *After No. 7 is on |
| | | | | | Load increases |
| 9000 | 5200 | 6300 | 7400 | 27,900 | Before No. 11 recalibrates No. 12 |
| 9000 | 7200 | 4300 | 7400 | 27,900 | After No. 11 recalibrates No. 12 |
| | | | | | Load increases |
| 9000 | 7200 | 7200 | 7400 | 30,800 | Maximum load |
| | | | | | Load decreases |
| 9000 | 7200 | 3000 | 7400 | 26,600 | Before No. 11 decalibrates No. 12 |
| 9000 | 5200 | 5000 | 7400 | 26,600 | After No. 11 decalibrates No. 12 |
| | | | | | Load decreases |
| 9000 | 5200 | 1000 | 7400 | 22,600 | *No. 11 gives signal to shut down No. 7 |
| 9000 | 7200 | 5400 | 1000 | 22,600 | No. 7 reduces load, preparatory to timing off |
| 9000 | 7200 | 6400 | 0 | 22,600 | After No. 7 is off |
| | | | | | Load decreases |
| 9000 | 7200 | 3000 | 0 | 19,200 | Before No. 11 decalibrates No. 12 |
| 9000 | 5200 | 5000 | 0 | 19,200 | After No. 11 decalibrates No. 12 |
| | | | | | Load decreases |
| 9000 | 5200 | 1000 | 0 | 15,200 | No. 11 gets signal to shut down |
| 9000 | 6200 | 0 | 0 | 15,200 | After No. 11 is off |
| | | | | | Load decreases |
| 9000 | 3000 | 0 | 0 | 12,000 | Before No. 12 decalibrates No. 8 |
| 7000 | 5000 | 0 | 0 | 12,000 | After No. 12 decalibrates No. 8 |
| | | | | | Load decreases |
| 7000 | 1000 | 0 | 0 | 8,000 | No. 12 gets signal to shut down |
| 8000 | 0 | 0 | 0 | 8,000 | After No. 12 is off |
| | | | | | Load decreases |
| 1000 | 0 | 0 | 0 | 1,000 | Minimum load |

NOTE: All loads are in amperes at 250 volts.

*Loads given are with maximum load on No. 7 and represent the worst possible distribution of load.

When the load on converter No. 8 reaches 95 per cent of full load, the load-responsive-starting relay No. 1A on No. 8 machine operates through a time-delay starting relay to bring onto the bus the second machine in the sequence, No. 12 motor-generator set. Since the current-regulating relays, No. 57, are set to limit the load on the converter to 100 per cent of full load, it can be seen that the lower setting on the starting relay permits bringing the second machine on before the system voltage commences to fall.

When machine No. 12 closes its d-c. breakers, it takes the voltage control away from converter No. 8 and assumes load. The converter voltage is then controlled by its current regulating relays No. 57. With no increase of station load, motor-generator No. 12 would pick up a relatively small load which would not be sufficient to keep it on. To prevent this its current limit recalibrating relay, No. 95, is arranged to decalibrate the current regulating relays on converter No. 8. This causes the rotary converter to reduce its load approximately 2000 amperes, or 25 per cent. This load, together with additional load which may come on, is picked up by motor-generator No. 12 until at 6300 amperes, its current limit recalibrating relay picks up to recalibrate the current regulating relays on converter No. 8 again. The converter then carries 100 per cent load and No. 12 motor-generator continues to absorb the oncoming load until it reaches 95 per cent of full load.

At this point, the load responsive starting relay No. 1A on No. 12 motor-generator functions to start the third machine in the sequence, No. 11, after a time delay. As soon as motor-generator No. 11 gets on the bus, it assumes control of station voltage and takes this control away from machine No. 12. Thus, rotary converter No. 8 and motor-generator No. 12 are being controlled by their respective current regulating relays and motor-generator No. 11 has its voltage controlled by voltage regulating relay No. 58. To insure that No. 11 machine will pick up enough load to stay on, its current limit recalibrating relay, No. 95, functions to decalibrate the current regulating relay on No. 12 machine by approximately 2000 amperes or 25 per cent. As the load builds up further, No. 12 machine is again permitted to assume full load as limited by its current regulating relay.

When the load on No. 11 machine exceeds 95 per cent of full value, its load responsive starting relay, No. 1A, causes rotary converter No. 7 to be started after the expiration of a short time delay. This machine is not paralleled with the others in the station but, instead, feeds the network through a separate group of feeders on a section of the main bus. This section is automatically split off by opening of the bus tie breakers when the converter is closed onto the bus.

With No. 7 converter on, voltage control is left with No. 11 machine as before and the voltage balancing relay No. 60 of converter No. 7 balances the voltage of its section of bus against that of the main bus and holds the voltage approximately two volts higher than the main bus. This results in converter No. 7 taking a little more than its share of the load and insures its taking enough load to stay on.

If for any reason the average feeder end voltage should become more than two volts low, the voltage regulating relay, No. 58 on No. 7 converter, will take control away from No. 60 balancing relay and will maintain, within the limit of No. 7 machine capacity, the average feeder end voltage at two volts below normal.

With decreasing load the machines are shut down in the reverse order from coming on. Machine No. 11 will reach its light load point before converter No. 7 and is arranged to give No. 7 the signal to shut down. No. 7 first closes the bus tie breakers and then reduces its load down to the setting of its own light load relays, that load being assumed by machines No. 11 and No. 12. Converter No. 7 then "times off" in the usual manner.

Further reduction of load shuts down machine No. 11 and still further reduction shuts down machine No. 12. Rotary converter No. 8 is not arranged with load-responsive starting and stopping since it is required on the bus at all times to maintain the net-work voltage and the system neutral at this point.

Provision is also made for starting the next machine in the sequence if the last machine called for by the load is held off by protective devices or manual control switches. The next machine then does whatever the disabled machine would have done in the way of load shifting and voltage control.

In coming back on the bus after a system outage, it is not permissible to allow converter No. 8 to be connected to the bus below 140 volts which is its lowest regulating point. In this case the bus undervoltage relay, although permitting No. 8 machine to complete its starting sequence to the point where it is ready to be connected to the bus, functions to start both motor-generator sets as fast as power supply conditions permit. As soon as the motor-generators, together with other stations, have raised the bus voltage to 140 volts or more, rotary converter No. 8 is connected to the bus and boosts the system voltage to the limit of its ability. At approximately 210 volts converter No. 7 will also be brought on the bus. This should raise the net-work voltage to approximately normal provided the other units on the system have started properly.

By means of pilot-wire remote-control, the system load dispatcher at Twelfth and Locust Streets may start or stop any machine. Since he has an indication of the load being carried by each machine and average feeder end voltage, this feature is of great value. It permits him to adjust, within limits, the Edison network load between the 25-cycle and 60-cycle systems in accordance with general system conditions.

### MOTOR-GENERATORS

Except for the load-responsive starting, and voltage and load-regulating schemes described above, the control for both motor-generator sets is similar to installations previously described before the Institute. The synchronous motors are started by throwing onto the line through reactors, the reactors being shunted out when the machines have reached approximately synchronous speed. The field is applied at the time of transfer and upon equalizing the bus and machine voltages, load is applied to the d-c. generators. The sets are of the differential compound type, normally operated with the series field shunted by an automatically controlled circuit breaker. The control is arranged and the sets are suitable for re-synchronizing under load in the event of a temporary power interruption.

### CONVERTER NO. 7

The booster-type synchronous converter No. 7 is arranged for *Y*-delta, starting by oil circuit breakers on the high-voltage side of the transformer. Correct polarity is established by temporary reversal of the field. This machine is connected to the bus through cushioning resistors which are arranged to give two-step operation. When the voltage of No. 7 machine and the station bus have been properly equalized the resistor breakers No. 73 are closed. After a short time delay, line breaker No. 72 positive is closed and after a further time delay, No. 72 negative is also closed. Thus only one step of resistance is shunted at a time. The closing of No. 72 negative is followed immediately by the closing of the neutral breaker No. 71 and the opening of the bus tie breakers No. 24. This sequence, in addition to giving two-step resistor operation, prevents lowering of the net-work voltage at the ends of the feeders connected to this section of the bus and allows ample time for the converter voltage to be adjusted properly.

### CONVERTER NO. 8

Synchronous converter No. 8 is a shunt-wound, 2250-kw., three-wire machine with high-voltage, revolving-field booster; the scheme of connections being shown in Fig. 4. The converter has the customary series and shunt commutating fields. The booster is provided with a double armature winding so connected that with a given direction of excitation on the field, the voltage of one winding will be in the "boost," and the other in the "buck" direction. The winding in use under any particular condition will depend upon the position of the tap switches. The high-voltage neutral is formed at the common point of the booster windings. The transformer is of the air-blast type and is provided with an extended winding having four ten per cent taps. Connections between the transformer taps and the booster windings are made by means of tap switches which are triple-pole oil circuit breakers.

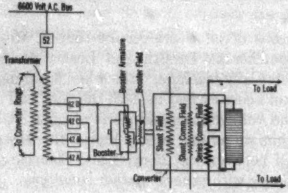

FIG. 4—SCHEME OF CONNECTIONS OF WINDINGS, NO. 8 CONVERTER

FIG. 5—CONTROL BOARD FOR NO. 11 AND NO. 8 MACHINES, BLOWERS, INCOMING FEEDERS AND COMMON MACHINE CONTROL

The control boards for machines No. 8 and No. 11 are shown in Fig. 5.

The control scheme used on converter No. 8 is in many respects new and novel and for this reason a rather full description will be given.

If we assume system conditions to be normal with bus voltage at normal value and machine No. 8 to be held off by the opening of master switch No. 5 the starting operation will be initiated by the closing of this switch which acts to energize the time-delay starting relay. After the expiration of the time interval for which this relay is set, the master contactor No. 4 will be closed provided line and machine conditions are proper as indicated by the protective devices. The oil circuit breaker closes immediately to energize the converter transformer and the motor-driven sequence switch No. 34 starts to revolve. This permits No 42A tap switch to close thereby closing the *Y* of the transformer through the booster windings and impressing half voltage on the converter.

While the converter is coming up to speed No. 34 sequence switch is stopped but restarts when synchronous speed is reached, as indicated by synchronous speed relay No. 13. This permits field-flashing contactor No. 31 to close and energize the field from a small motor-generator set to properly polarize the converter. When correct polarity has been established as indicated by field-changing relay No. 93, the field flashing contactor is opened and the shunt field contactor No. 41 is closed to make the converter self-excited.

When full field is reached as indicated by field relay No. 40 further movement of No. 34 sequence switch is permitted which opens the low-voltage tap switch

No. 42A and closes the highest-voltage tap switch No. 42D. The booster field is then applied by the closing of the booster field contactor, No. 41C, and the auxiliary commutating field is excited by the closing of auxiliary commutating field contactor, No. 41A.

The voltage of the converter is then equalized with the bus voltage by the operation of voltage equalizing relay, No. 91, which has control of the booster field rheostat at this time. When the voltages are properly equalized, voltage balance relay No. 60 permits the load limiting resistor breakers, No. 73, to close. The closing of No. 73 breakers is followed immediately by the closing of the line breakers, No. 72. Upon the closure of circuit breakers, No. 73, the control of the motor-operated booster field rheostat, No. 70, is given to the voltage and current regulating relays. These relays operate to hold the voltage of No. 8 machine within 1¼ volts of normal value on the pressure wire bus until the converter is loaded to approximately 8700 amperes. At this point the current regulating relays No. 57 take control and hold the current on this machine at an average value of 9000 amperes.

### TAP CHANGING

When voltage reduction is necessary, the booster rheostat is run in the "buck" direction. When maximum buck is reached as indicated by limit switches on the booster rheostat and relay No. 60A, which balances the booster voltage with a-c. line voltage, a circuit is made to close tap switch No. 42C. It will be noted from the diagram, Fig. 4, that this connects the two ends of the booster across high-voltage taps on the transformer. As soon as No. 42C closes, No. 42D is opened and the converter is operating on the second transformer tap with the booster field rheostat in the maximum boost position. The transition from buck to boost is accomplished by the use of a double winding in the booster. When the tap change is made a shunt field contactor No. 41D is closed to shunt a section of the resistance in the shunt field of the converter in order to increase the shunt field current sufficiently to correct for the change from buck to boost on the booster with the attendant change from generator to motor action on the converter. This action is simultaneous with the reversal of the auxiliary commutating field of the converter. These operations tend to raise the voltage of the converter slightly so that the booster rheostat tends to run out of the maximum boost position due to the action of the current regulating relays. This prevents "pumping" of the transfer equipment at the tap point.

If further voltage reduction is necessary, the booster rheostat moves out of the boost position and finally reaches approximately maximum buck. At this point, as indicated by rheostat position and No. 60A relay, tap switch No. 42B is closed and No. 42C opened to connect the converter to the next lower tap. The reversal of the booster, the reversal of the auxiliary commutating field, the action of shunt field contactor No. 41D and the backing off of the booster rheostat are accomplished in identically the same manner as previously described.

The necessity for further voltage reduction will force the converter to the lowest tap by an operating sequence similar to that above which closes tap switch No. 42A and opens No. 42B. Demand for still lower voltage will force the booster rheostat into the maximum buck position and if this is not sufficient to reduce the load on the converter to a proper value the station d-c. undervoltage relay, No. 80A, will function to disconnect the machine from the bus. The converter will continue to run, in readiness to again assume load as soon as voltage conditions permit.

When the bus voltage rises above the setting of undervoltage relay No. 80A this relay will function to again connect the converter to the bus. The current regulating relays, which have control until the bus voltage is normal, which will be with tap switch No. 42D closed, function to run the booster rheostat to the maximum boost position. At this point, as indicated by rheostat position and booster voltage relay No. 60A, tap switch No. 42B will be closed and No. 42A opened. Simultaneously the auxiliary commutating field on the converter is reversed and shunt field contactor No. 41D is dropped out to insert resistance in the shunt field to again compensate the converter for the booster change, this time from boost to buck rather than from buck to boost as previously described. This compensation is sufficient to lower the converter voltage slightly and thereby cause the booster rheostat to run toward the boost position which, it will be noted, is the reverse of the condition when "tapping down." Further decrease of converter load or increase of bus voltage will cause the tap changing equipment to "tap up" until the highest tap is reached, each tap change following the sequence outlined above. When the highest tap is reached, the converter is regulated to hold proper voltage or current in accordance with the indications of the voltage and current regulating relays.

### PROTECTIVE FEATURES

The size and importance of this converter unit warrant extensive protective equipment and an endeavor has been made to protect against all operating contingencies. Most of these protective features are of a standard type and, for this reason, the descriptions of these features will not be detailed.

1. Starting on single-phase or incorrect phase rotation is prevented by single- and reverse-phase voltage relay No. 47.

2. Starting on low a-c. voltage is prevented by undervoltage relay No. 27. If low voltage occurs while the machine is running, undervoltage relays No. 27A shut the machine down.

3. Correct position of the brushes is assured by

interlocks on the brush-operating mechanism which prevent starting with the brushes down or closing of the d-c. breakers with the brushes up.

4. If the starting sequence is not completed within a predetermined time interval, starting protective relay No. 48 will shut down and lock out the unit.

5. The failure of field excitation will be indicated by field relay No. 40 which is in series with the converter shunt field or by field relay No. 40A which is in series with the booster field. Either of these devices will operate through an auxiliary relay, No. 40X, to shut down the unit and hold it off awaiting an inspection.

6. Reverse power as indicated by reverse-current relay No. 56 opens the d-c. line breakers No. 72 to insert the load-limiting resistors in the circuit.

7. Overheating of any bearing will trip its bearing-temperature relay, No. 38, to shut down and lock-out the unit.

8. Overheating of the load-limiting resistors operates resistor-temperature relays No. 28 to shut the machine down. When the resistors have cooled sufficiently No. 28 relays permit restart.

9. Flashover or grounded windings will operate grounding protective relay No. 64 to shut down the converter and prevent its restart.

10. Overspeed causes the speed-limit switch No. 12 to operate, shutting down the machine and tripping the neutral circuit breaker. This guards against the possible failure of one side of the line to open. The unit must be inspected before a restart can be made.

11. A-c. power failure is indicated by undercurrent relay No. 37 and reverse-power relay No. 56 which operate to shut down the converter. Restart is permitted on restoration of power as indicated by undervoltage relay No. 27.

12. A-c. overload operates the overload relays No. 51 which trip the line oil circuit breaker No. 52. At the same time, locking-out relay No. 86 is tripped and prevents restart.

13. Correct polarity is insured by flashing of the field from field flashing generator No. 34E and possible connection to the bus with reversed polarity is prevented by voltage directional relay No. 91.

14. Overheated d-c. windings will operate d-c. thermal relay No. 68 to reduce the load to half of full load value by decalibrating the current regulating relays No. 57. At the same time a circuit is made to start the next machine in the sequence. If the converter should continue to heat thermal relay No. 68A will trip lockout relay No. 86 to shut down the machine so that an inspection is necessary before a restart can be made.

15. Excessive load unbalance as indicated by overheated neutral copper operates thermal relay No. 68N to lock out the converter.

16. Protection against overheating of the a-c. windings is obtained in two ways. Two a-c. thermal relays, No. 49, which operate on current input to the unit protect against possible overheating from moderate overload or single-phase operation by opening master contactor No. 4 and shutting down the unit until it has cooled sufficiently to permit restart.

Thermostats located in the air discharge paths from the booster and transformer operate to reduce the load to 50 per cent of full load. If the unit continues to overheat, additional thermostats shut it down and lock it out.

### CONCLUSION

This equipment has now been operating fully automatic for somewhat over a year and its operation has been very successful. During the initial starting up period there were many difficulties encountered, and subsequently others arose, but they were all carefully studied and remedied. Here again, as previously, both the operating company and the manufacturers benefited by the experience gained through solving the problems which arose.

There have been quite a few system disturbances with this equipment in service and in practically every case the automatic control appeared to function correctly. In most cases, of course, there was no one at the station at the time of the trouble and the performance of the apparatus had to be determined from the chart records. However, during the disturbances when, by chance, men were at the station, many observations were made and a great deal of confidence gained. In one case in particular, when the Keokuk transmission circuits were completely disabled by a tornado and the load thus released was suddenly thrown on the steam plants, this control gear operated admirably over a wide range of frequency and a-c. voltage and through severe d-c. load fluctuations until the system was again stabilized. At the time of the disastrous tornado of September 29th, 1927, none of the machines at St. Charles Street even dropped their load, although the a-c. system was subjected to many severe short circuits and grounds.

With improvements being made rapidly in automatic control apparatus, it is felt that increasingly complicated operations will be controlled automatically and still greater reliability obtained in the future.

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## Discussion

**Caesar Antoniono:** I have been enthusiastic about automatic operation since the early days and I still am.

We have 18 automatic equipments on interurban service totaling 20,000 kw., leaving at present 5300 kw. of manually-operated equipment, in 4 stations.

I have been in contact with the operation of several other of our affiliated companies and have no reason to change my mind. It has reduced the operating cost and made it possible for us to better our distribution of power and voltage, without a prohibitive capital investment.

**H. Bany:** (by letter) It is interesting to note that no stand-by batteries are used on the Union Electric Light and Power Company's 250-volt Edison system. Although this is undoubtedly to a large extent due to the fact that this company has been able to avail itself of the increased reliability of its a-c. supply, due to the use of two separate supply sources, still the elimination of the stand-by battery must further be regarded as an expression of confidence in the automatic station for this exacting service.

In the St. Charles St. Substation no effort or expense was spared in the design of the automatic switching equipment to give the station the reliability and the voltage and load-control features it required as a base-load station. It is felt, in this case, that this has been well worth while in view of the results desired and obtained. It should be realized, however, that the number of special features incorporated in an automatic switching equipment should be a function of the requirements which must be met, and if the requirements are such that a simpler equipment will fulfill them, the simpler equipment should be used. This not only results in a lower first cost, but also eliminates the extra maintenance.

It is also of interest to note the creditable performance of the synchronous converter equipment during the low a-c. voltage and frequency period when the Keokuk transmission line was disabled by a tornado. Ordinarily it would be expected that the motor-generator sets alone would be of value at such a time but here the synchronous converter exceeded its expectations.

**H. R. Summerhayes:** It may be of interest to discuss briefly the various types of machines and schemes of control for use on Edison Systems. Under normal conditions, of course, the voltage range obtainable with the standard type of machine is sufficient to take care of normal operating conditions.

It is important, however, that the apparatus on the Edison System be arranged so that the load can be picked up without difficulty in the case of a partial or complete outage. In order to accomplish this, it is necessary either to arrange the machines so that stable operation can be obtained at any point from zero to full voltage or to arrange the circuit so that the current output from the machine will be limited when it is operating at or about normal voltage.

With the motor-generator sets this can be accomplished by the use of separately excited fields on the d-c. generator, the voltage and current output from the machine being limited by regulating devices operating on the field circuit. An alternative arrangement to the straight separate excitation is found in the scheme which uses a small generator in the field circuit, the voltage of which opposes the applied voltage. Thus, building up voltage on this counter e. m. f. generator will reduce the field current to the desired value. The voltage of the counter e. m.f. generator is controlled by current and voltage regulators which limit the current or voltage output from the main d-c. generator. The third method for motor-generator sets is found in the differential series field generator. The fields on this machine are wound so that the series field opposes the shunt field which makes the machine inherently load-limiting. The excitation applied to the shunt field is obtained from the generator terminals in series with a separate source of power which is usually obtained from a small direct-connected exciter, this exciter also being used to excite the fields of the synchronous motor. This combination of fields results in a design which will permit the d-c. generator to operate at any voltage from zero to full voltage and which is inherently load-limiting, thus giving a machine which will require a minimum of control to give the desired results. Contact-making ammeters and voltmeters may be used with these machines to limit the current or voltage to definite values.

Synchronous converters may be arranged to operate in the starting or Y connection which, of course, will give practically 57 per cent of normal voltage. In this case, of course, it is necessary to disconnect the latter from the line before changing over to running or delta connection. Arrangements may be made also for partial voltage reduction by transformer taps with or without arrangement for changing taps under load. Where transformer taps extend over any appreciable voltage range and the changing of taps under load is required it will be necessary to use a scheme involving the use of a booster or regulator in order to obtain a smooth transition.

An alternative method consists of using a standard converter operating at full voltage using a current-limiting resistor in series with the machine, the resistor being designed so that current output from the machine will be limited to a safe value. This resistor is divided into a number of steps, each of which can be short-circuited by a circuit breaker, the steps being designed so that the maximum safe value of operating current will not be exceeded when one block of resistance is short-circuited.

Where the load-limiting resistor is used it is, of course, possible to connect the converter to an entirely dead system, whereas with the other schemes mentioned for the converter, these machines, of course, cannot be connected to the system until the system voltage has been raised to this amount by means of other machines which may be connected to the system at a lower voltage.

I should like to ask a question with regard to operation of the system as supplied from 60-cycle converters and 25-cycle converters. In some cases it has been feared that such operation might result in trouble with burning of brush-rigging in case of a short-circuit on one of the a-c. systems; that the rotary converters would feed back through the d-c. system from the other a-c. system. It has been feared that in larger systems such feed-backs would be disastrous and, in fact, I have known of brush-holders being burned off on a number of converters. I should like to ask what precautions are taken against occurrences of this sort.

**H. L. Wallau:** In Cleveland we have a d-c. district similar to that in St. Louis, being slightly smaller in area, with a demand of about 35,000 kw. The number of stations is 4 instead of 8. One of these stations is an old generating plant and in winter supplies steam heat through geared turbine-generators with direct current as a by-product. There are also 3 motor-generator sets, and a 400-kw., 60-cycle rotary converter. Of the other 3 substations, the first put in service contains motor-generator sets and rotaries, all manually controlled, the newer and larger machines being all a-c. start. In our Public Square Station we have six 2000-kw. (nominal) rotary converters of the booster type, also manually controlled. Our latest station includes three nominal 3250-kw. units of the automatic type. Operators are maintained here because in addition to supplying direct current there is some important a-c. distribution from this station, and a large battery is installed as well. The operator selects the d-c. bus on which he desires to operate the converter and then through his control switch he gives the starting impulse and the rest of the operation is automatic. These machines are protected with load-limiting devices and tests indicate that they function properly, although no severe disturbances have occurred which have required their functioning for any long period of time.

The automatic equipment has operated satisfactorily. There have been very minor mechanical troubles which have been found on inspection and corrected, but nothing that would tend to discredit the equipment in any way.

**George Cree:** (by letter) A more complete description of the operation of the machine described as Converter No. 8 might give a better understanding of the control scheme which is used.

As shown in the diagram, the main converter transformer is equipped with an extended winding with four taps, each approximately 10 per cent, so that when the total primary winding is used the voltage applied to the converter is decreased by 40 per cent which is equivalent to 160 volts on the d-c. side of the converter. In addition to this, approximately 7½ per cent further decrease in d-c. voltage can be obtained by operating the booster with the field excited in the full buck direction. This will give a minimum full-load voltage of approximately 150 volts.

Therefore, in case of low voltage on the Edison System this converter can be connected to the system at approximately this voltage.

When connected to the system in this manner it is of course necessary to pass through the various taps on the transformer keeping a smooth voltage range so that the machine will not tend to pick up or drop any appreciable increment of its load. The booster winding is designed so that the voltage generated in the winding at full buck or full boost will be equal to the voltage across the transformer taps. This winding is also divided in two halves, the middle point of the booster winding forming the *Y* point for the primary of the power transformers. For instance, if the converter is operating at full boost on tap *A* and it is desired to increase the voltage, the switches which connect the other end of the booster winding to tap *B* may be closed, as the voltage generated in the total booster winding will be equal to the voltage across the transformer tap. Then if the switches connecting the booster to tap *A* are opened the current will flow through the other half of the booster winding in the opposite direction to the previous flow of current, thus giving a full buck condition instead of the previous condition of full boost. Inasmuch as the transformer voltage on tap *A* plus the boosting effect of the converter will be the same as the transformer voltage on tap *B*, minus the bucking effect of the booster, the a-c. voltage of the machine will not be changed.

The change in power-factor conditions resulting from changing the booster from boost to buck position makes it necessary to readjust the shunt field of the converter as mentioned in the paper.

**E. L. Hough:** Mr. Summerhayes has brought up the question of the operation of 60-cycle and 25-cycle systems when tied together through a d-c. network. The Union Electric Company does not use 25- and 60-cycle machines in the same station. The stations are all tied together through the feeder networks and the shortest distance between the two systems is approximately three blocks, so that no difficulties whatever have been experienced in operating the 25- and 60-cycle systems tied together through the network. In fact, it might be brought out that we really have more than the two supply frequencies and two stations at each frequency. The Cahokia plant is arranged so that bus sections may be isolated in case of trouble, and during such time we may have the equivalent of about three plants at Cahokia, since the bus may be split.

**O. J. Rotty:** I should like to point out just a few things with regard to Table I. I wish to bring out the way in which the capacities are balanced. It will be seen that the capacity in motor-generator sets totals 78,000 amperes, whereas the converter capacity totals 68,400, making them almost equally divided. Also note that the total of 60-cycle machines is 71,400 amperes and the total of 25-cycle machines is 75,000. Here again there is practically an equal balance of machines, but in this case the division is between the 25- and the 60-cycle systems.

Our Edison system peak of 1926 amounted to 129,000 amperes, while last December we exceeded that by approximately 6500 amperes; so it will be seen that we are approaching the capacity of the present machines. However, some of the old machines which were supplanted by the automatics are still in condition to run in emergencies and are considered as stand-by equipment. These machines are not included in the data of Table I.

# Protection of Supervisory Control Lines Against Over-Voltage

BY EDWARD F. W. BECK[1]

Associate, A. I. E. E.

**Synopsis.**—*Supervisory control lines used in the remote, or automatic control of electric plants are subject to overvoltages dangerous to insulation and to operators. These overvoltages may be caused by lightning, crosses with the power lines, or induction from them. Open wire control lines are influenced by all of these, cables with grounded sheaths are immune to disturbances caused by lightning or other electrostatic induction, and are more or less safe from crosses. The ordinary cable, however, is still subject to high voltages by electromagnetic induction when a fault occurs on the power line.*

*These voltages may be dangerous not only to apparatus, but also to the cable insulation. Protection by means of lightning arresters is therefore necessary. Calculations show that even if the apparatus locations are protected, high voltages may occur along the line if the transmission line fault is between stations. This may cause a cable failure. It may, therefore, be advisable to protect the cable at certain intervals.*

*Supervisory control protectors may be called upon to discharge heavy currents of appreciable duration. This requires extremely sturdy arresters. The requirements are met by a spark-gap of special design in argon at a reduced pressure.*

*Specially made cables will shield the line against extraneous disturbances. In large installations, the use of such cables may be worthy of consideration.*

SUPERVISORY control and remote metering for substations and small hydroelectric plants are widely used. In order to prevent insulation failures and consequent interruptions of the control, it is necessary to provide the control lines and apparatus with adequate protection against overvoltage. The wire lines over which the control is exercised are usually of considerable length. They are subject to overvoltage from several sources; hence protection in the form of lightning arresters is required to insure the continuous functioning of the system and to safeguard attendants from shocks.

The supervisory control line is usually of the same nature as a telephone lead, consisting of the necessary number of pairs of wires either strung in open wire lines or in cable. Complete metallic circuits are employed, the use of the earth as a conductor being avoided. The preferred mode of running the line where the number of circuits warrants it, is in a lead sheathed cable. Such cables with the sheath grounded are exempt from certain kinds of overvoltage disturbances, and the grounded metallic sheath mitigates the bad effects of others.

For the time being, consider an open wire line as it is exposed to more severe disturbances than is a cable. Overvoltages in such a line may occur from the following causes:

1. Atmospheric electricity and lightning discharges.
2. Direct crosses with high-voltage lines.
3. Potentials above ground caused by electrostatic or electromagnetic induction from neighboring power lines.

The hazardous voltages caused by atmospheric electricity will not be discussed here. This is a subject which has received considerable attention in the literature in connection with transmission lines. The reaction of an open wire line to lightning is similar to that of any transmission line. This phase of the problem is discussed in the first two references of the appended bibliography.

Direct crosses with high-voltage lines may occur since the control line is usually strung on the same poles with the power line. The best safeguard against damage in that event is the use of a high-voltage fuse in the control line together with a protector of sufficient discharge capacity to rupture the fuse and clear the apparatus from the charged control line. If the control line is strung in cable, the lead sheath, unless it is fused by the short-circuit power current, will keep the high voltage from the line.

This discussion relates principally to overvoltages due to induction. These are of considerable importance in connection with supervisory control lines, or others of a similar nature. The control lines run between power stations and therefore usually parallel the transmission lines which connect the stations, sometimes strung on the same poles with them, sometimes on separate pole lines, but never very far away. They are thus continually under the influence of the voltage and current conditions existing in the transmission line.

In the following discussion of induction, approximations will be generally resorted to, neglecting such things as the effect of the size of the wire, the configuration of the lines, or the shielding effects of nearby earthed conductors. Exact calculations will not be attempted. Hazardous voltages of the order of hundreds or more volts are the objects of interest. It is therefore not necessary to be as particular in the assumptions and calculations as would be the case were telephone or telegraph lines concerned in which very small disturbing voltages might cause false signals or interruptions of the service.

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If the line is open wire, disturbances may be caused either electrostatically or electromagnetically. Electrostatic induction will occur in the following way:

In Fig. 1, $A$ is a conductor charged to a certain voltage $E_A$, and $B$ is a nearby conductor, such as a supervisory line entirely insulated from ground. Between $A$ and earth, $G$, there will be an electrostatic field due to the potential $E_A$. Some of the electrostatic lines between $A$ and $G$ will terminate on $B$, imparting to it a certain charge and therefore a potential above ground.

For an approximate solution, with the total number of lines of force between $A$ and $G$ known, a parallel plate condenser may be substituted for line and ground, this condenser having the same number lines of force between its plates as pass from $A$ to $G$, when the plates are at a difference of potential $E_A$. In the same manner condensers may be inserted between $A$ and $B$, and $B$ and $G$. The capacities of such hypothetical condensers are known as the direct capacity of $A$ to ground, $A$ to $B$, etc. Thus, Fig. 1 may be replaced by Fig. 2. This facilitates the derivation of the induced potentials. Calculating the impedances of the circuit involved, the charging currents and the potentials may be found.

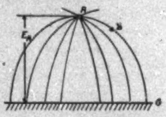

FIG. 1—DIAGRAM SHOWING HOW VOLTAGE IS INDUCED ELECTROSTATICALLY ON SUPERVISORY LINE

The potential to ground which $B$ takes up is:

$$V_B = E_A \frac{C_{AB}}{C_{AB} + C_{BG}}$$

The capacities involved may be calculated if the spacing between conductors to the earth is known. This subject is treated by Schrottke, Eggeling, and Jaeger, (see bibliography). An approximate solution given by Jaeger is,

$$C_{AB} = 2.42 \left( \frac{a\,b}{a^2 + b^2 + c^2} \right) 10^{-3}\ \mu\text{ f. per mile.}$$

If $a = 40$ ft., $b = 20$ ft., and $c = 55$ ft.

$C_{AB} = 0.00038\ \mu$ f. per mile.

The capacity $C_{BG}$ of the ordinary open wire line will be of the order of 0.0097 $\mu$ f. per mile.

Then $V_B = 0.0375\, E_A$.

If $A$ is charged with an a-c. voltage of 22,000 above ground, $V_B = 22{,}000 \times 0.0375 = 825$ volts r. m. s. or 1160 volt peak.

As the spacing between $A$ and $B$ is increased, the value of $C_{AB}$ and, hence, the value of $V_B$ decreases rapidly, approaching a small constant value for spacings of about 150 ft.

If $B$ is solidly grounded, $V_B$ will be zero, the disappearance of $V_B$ being accompanied by an increase in the charging current from $A$. On the other hand, if $B$ is grounded through a very high impedance, such as the body of an attendant, the voltage $V_B$ may be high. If the total impedance of the circuit $A$, $C_{AB}$, $B$, attendant, ground is sufficiently low, as it may be if $C_{AB}$ and $C_{AG}$ are large, which will be the case if the parallel is long, enough current may flow through the attendant to be dangerous. It is also possible that punctures of apparatus insulation will occur. For this reason, overvoltage protectors are necessary on a line subject to electrostatic induction, neglecting for the moment the additional requisite of safeguarding against electromagnetic induction. Low-voltage lightning arresters will hold this induced voltage down to the discharge voltage of the device.

The above discussion deals with what is in effect a single-phase ground return power line, such as a railway trolley, for instance. On a three-phase power system, the conditions are similar provided the phase voltages are unbalanced. Ordinarily, the configuration of the wires of the transmission line and the location of the supervisory line will be such that the electrostatic field resultant of the three phases, when the voltage is balanced, is small; in that case, there is no appreciable overvoltage on the control line. Fig. 3 shows the spacings between transmission and supervisory lines for which the normal electrostatically induced voltage is below 300 volts. The curves are plotted for a horizontal configuration of the transmission line. If a triangular configuration is used, the conditions will be better; if a vertical configuration is used, the induction will be about the same as for a horizontal configuration unless the control line is directly below the power line, in which case the influence of the lowest transmission line conductor will be quite marked. For the purpose of this discussion, it may be assumed that the normal electrostatic field is negligible. If the relative positions of the power and control lines are such that high voltages are steadily induced in the latter during the normal operation of the power line, these must be removed from the control line by drainage devices other than lighting arresters because the continuous discharge of arresters would make the control line inoperative.

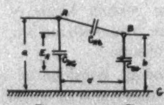

FIG. 2—SCHEMATIC DIAGRAM OF CONDITIONS IN FIG. 1

If a fault occurs on the transmission line so that the voltages are no longer balanced, there will be a pronounced electrostatic field causing an induced voltage to appear on the control line. If the substitution of condensers is made as outlined in Fig. 2, the distribution of charging currents and the induced voltages set up in the control line may be derived. The maximum induction takes place when a ground fault occurs on one phase of the transmission line in which case the electrostatic field between the ungrounded phases and the earth is most intense.

Considering a three-phase power line with ungrounded neutral, assuming one phase dead grounded through a fault, and assuming that the voltage of the grounded phase to earth is zero, the calculation by means of equivalent condensers leads to the conclusion that the disturbing field is approximately proportional to the vector sum of the line voltages between the sound and grounded wires, in the case of either a delta or a $Y$ system. So the disturbing system may be replaced by a single wire having a potential above ground equal to the above mentioned vector sum of voltages and the case is then as pictured in Fig. 2.

Let us assume a three-phase delta or $Y$ system with ungrounded neutral and a line to line voltage of 22,000 with one phase accidentally grounded—a case paralleling Fig. 2.

$\vec{E}_A = \vec{E}_{1-2} + \vec{E}_{1-3} = \sqrt{3} \times E_{line} = \sqrt{3} \times 22{,}000 = 38{,}200$, from which the crest value of the induced voltage is then: $V_B = 0.0375 \times 38{,}200 \times 1.41 = 2020$ volts.

A ground on an ungrounded system may stay on for some time before it is cleared, increasing the hazard. If the ground is a high resistance one, the transmission line voltage is not so badly unbalanced and the disturbance is less severe.

If simultaneous grounds occur on two phases, the induction is also less severe. The electrostatic field is then that due to one line wire only,—the sound one. The disturbance is then only $\frac{1}{\sqrt{3}}$ times as great as in the above mentioned case. A dead ground on one phase is the limiting case and therefore the one to be provided for.

On a system operating with the neutral grounded an accidental ground will not cause so high an electrostatic voltage on the control line as on an ungrounded system. In this case, the field will be proportional to the vector sum of the voltages to neutral of the sound phases:

Thus $\vec{E}_A = \vec{E}_{line} \frac{1}{\sqrt{3}} + \vec{E}_{line} \frac{1}{\sqrt{3}} = \frac{E_{line}}{\sqrt{3}} \times \sqrt{3} = E_{line}$.

Considering again a 22,000-volt system, $V_B = 0.0375 \times 22{,}000 \times 1.41 = 1170$ volts crest compared to 2020 volts for the system operating with an ungrounded neutral.

For simultaneous grounds on two phases, the field is proportional to the voltage from line to neutral, *i. e.*,

$$V_{AB} = 0.0375 \frac{22000}{\sqrt{3}} \times 1.41 = 675 \text{ volts peak.}$$

On a system operating with the neutral grounded, a third harmonic or multiples thereof will cause a steady induction. The $3n$ harmonics are in phase between the line conductors and the neutral; hence they will originate an electrostatic field between line and ground proportional to the harmonic voltage to neutral, neglecting the increased capacity due to the three line conductors being in parallel. The $3n$ harmonics should be avoided. In a poorly designed system the third harmonic can be 30 per cent of the fundamental, in which case there would be a steady voltage on the control line for the above-considered 22,000-volt system, of $2020 \times 0.3 \times 3 = 3800$ volts. A third harmonic of 3 per cent only will induce 380 volts above ground on the control line and this potential will be on the line as long as the transmission line is energized, probably continually discharging the protectors and interrupting the control. Therefore, $3n$ harmonics should be drained out of the system or else the control line must be moved sufficiently far away from the transmission line to reduce the induced voltage below the breakdown voltage of the protectors. If this is not possible, special protective measures must be taken, such as the use of drainage devices already mentioned.

High voltages may be induced in the control line by transients in the transmission system. These voltages will be proportional to the transient voltage; so they may be exceedingly high, especially if the transients are due to lightning. When a fault occurs on the transmission line, surges are generated before a steady state is reached. On an ungrounded system, a solid ground may cause a surge of twice the normal voltage; an arcing ground may cause repeated surges of three and one-half times the normal voltage. On a grounded system conditions are not so bad, as the surges caused by accidental grounds will usually not be more than twice the normal voltage.

The presence of grounded conductors near the control line will materially reduce the induction due to the increase in the capacity to ground of the control line, $C_{BG}$ in Fig. 2. These conductors may be in the form of continuous rows of trees, a ground wire, or the like. By far the most effective manner of shielding the control line against electrostatic induction due either to the transmission line or lightning is the running of the line in metallic sheathed cable with the sheath grounded. The line is then immune to such influences. If cable is used, the electrostatic lines of force terminate on the cable sheath and not on the control line conductors. Hence, considering only protection against overvoltage, regardless of other advantages derived from this method of installation, the use of cable for control lines is to be recommended. When the number of conductors in the line is so small that an open wire line is preferable to cable, other protection in the form of lightning arresters is essential to protect against electrostatic induction.

If there were not the possibility of electromagnetic disturbance and crosses with the transmission line, the use of sheathed cable would probably make it unnecessary to use protectors, provided the sheath were grounded at many points. The lead sheath of a cable, unfortunately, does not provide a perfect shield against electromagnetic induction, although it may reduce its effect appreciably.

Consider a single-phase transmission line with ground return and a neighboring control line consisting of a single isolated wire paralleling the transmission line. Suppose, also, that the transmission line is grounded at the far end so that a current flows around the loop consisting of transmission line and earth. This current will be attended by a magnetic field, part of which will cut the area enclosed by the control line and ground, inducing in the line an e. m. f. If the control line is grounded at both ends, a closed loop is formed in which a current will flow. The two lines together may be likened to a transformer of which the transmission line is the primary and the control line the secondary. The induced e. m. f. in the control line is dependent upon the total magnetic flux cutting the area between it and the ground, this magnetic flux, in turn, being a function of the area enclosed between the transmission line and ground return current. In order to calculate the induction, it is necessary to determine what these areas are. The length of the exposure being known, this resolves itself into a determination of the ground current, and the distance between the lines and the path of the returning earth current. For this purpose, the conception of the so-called equivalent ground plane is necessary.

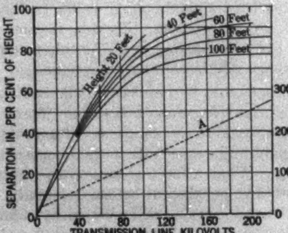

FIG. 3—SEPARATIONS REQUIRED BETWEEN POWER AND CONTROL LINES

These curves show separations necessary to keep the electrostatic induced voltage below 300 volts above ground during normal operation of the power line.

Dotted line shows the spacings used between phases of the transmission line.

Control line strung beneath transmission line.

When the current enters the earth from one electrode, it does not travel in a direct line to the other. It spreads out to a considerable extent in all directions, so that the cross-section of the current path is extremely large. Most of the current flows at a great depth. In order to make the calculations practical, it is necessary to assume a current path confined to a horizontal plane somewhere in the earth, the distance between it and the line being such that the flux included in the theoretical area so formed is of the same value as that actually generated by the transmission line current. This theoretical current-carrying plane is called the equivalent ground plane. It may be simply defined as the surface of a hypothetical earth with negligible resistance and a two-dimensional current distribution, this plane being at a suitably chosen distance below the actual surface of the real earth. There exists a considerable amount of experimental data to aid in the choice of this distance.

It is assumed that the ground current on leaving one ground electrode flows vertically downward to the equivalent ground plane; then follows it. The resistance on the path being assumed negligible, the ground resistance of the earth path is considered concentrated about the ground electrodes.

Having established what the circuit shall be, it is possible to proceed to the methods of calculating the electromagnetic induction. It can be shown under the above assumptions that the e. m. f. induced in a unit length of control line is expressed by this formula:

$$e = 0.00466 \times f \times \log\left(\frac{2h}{d}\right)$$

$e$ is the induced voltage per mile of exposure per ampere of current in the disturbing transmission line.

$f$ = is the disturbing frequency.

$h$ = is the height of the disturbing line above the equivalent ground plane.

$d$ = is the spacing between lines expressed in the same units as $h$.

The location of the equivalent ground plane below the surface of the earth is a more or less indeterminate quantity depending in the main upon the conductivity of the soil which in turn depends upon the nature of the soil, its moisture content, and the like. If the conductivity is high, or if there is a layer of conductive soil near the earth's surface, the equivalent ground plane will be near the surface. If the conductivity of the earth is poor, the equivalent ground plane will be deeper in the earth. Experience shows that the distance between the earth's surface and the equivalent ground plane may vary from a few feet to 2000 ft. Experience also shows, however, that in most cases the maximum depth that may be expected is approximately 500 ft., so that calculations made with this value for $h$ give in nearly every case values of induced voltage which are amply high. Moreover, as the depth of the equivalent ground plane is increased, the induced voltage increases less rapidly as shown in Fig. 4, which is reproduced from the article by R. Mitsuda and K. Kasai (see bibliography) so that for values of $h$ greater than 500 ft., the results will not be affected as much as may appear off hand. Moreover, there are usually mitigating factors present which, in actual practise, reduce the induction. Consequently we may use the

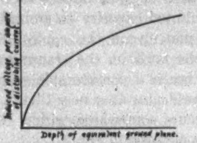

FIG. 4—VARIATION OF INDUCED VOLTAGE WITH DEPTH OF EQUIVALENT GROUND PLANE

value 500 ft. with safety and write the equation for induced voltage:

$$e = 0.00466\, f \left( \log \frac{1000}{d} \right) \text{ volts per ampere mile,}$$

where $d$ is in feet.

For convenience, we may express this equation in terms of 25- and 60-cycle induction:

$$e_{25} = 0.116 \log \frac{1000}{d} \text{ (r. m. s.)}$$

$$e_{60} = .269 \log \frac{1000}{d} \text{ (r. m. s.)}$$

for parallel exposures.

The variation of the induced e. m. f. $e$, with the spacing $d$, between the disturbing and disturbed lines is shown in Fig. 5. This curve is not accurate for spacing approaching $2\,h$. If the equation for $e$ is used, as given, the induction at a spacing of $2\,h$ would be zero, because in the derivation of $e$, assumptions have been made which bring this about. Actually, the induction persists to greater distances, theoretically to infinity.

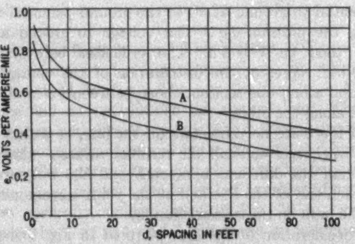

FIG. 5—E. M. F. INDUCED PER AMPERE-MILE AT 60 CYCLES

Curves show variation of e. m. f. with spacing between disturbing and disturbed lines.
Curve $A$, depth of equivalent ground plane, 1500 ft.
Curve $B$, depth of equivalent ground plane, 500 ft.

Considering protection against overvoltage, the potential of the control line to ground is the object of interest rather than the e. m. f. acting along the line. It may be well here to point out the differences between electrostatic and electromagnetic induction. In the former case, the induced voltage occurs between the disturbed line and ground. It is independent of the length of the exposure, being determined only by the capacity per unit length and by the disturbing voltage, while the amount of charging current is dependent upon the length of the exposure. In the case of electromagnetic induction, the e. m. f. is induced along the disturbed line and is a function of the length of the exposure and the disturbing current, while the current flowing in the wire is dependent upon the characteristics of the disturbed line. After establishing what the induced e. m. f. is, the control line may be considered as a circuit containing reactance and resistance depending upon the constants of the line, and a source of potential whose e. m. f. is the induced voltage.

In order to determine the potential to ground due to electromagnetic induction, consider the disturbed line by itself with a source of e. m. f, $E_B$, induced in it. If the control line is totally isolated from ground, the current which flows is chiefly a charging current. Its value is,

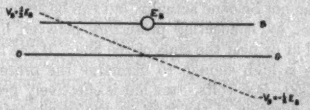

FIG. 6—DISTRIBUTION OF POTENTIAL ON LINE ISOLATED FROM GROUND

$$I = \frac{E_B}{Z = Z'}$$

where $Z$ is the impedance of the line, "the ground impedance being considered zero" and $Z'$ is the impedance between the line and ground consisting of the distributed capacity and resistance of the line to earth. $Z$ is small compared to $Z'$, so it may be neglected.

The voltage between line and ground at any point is dependent upon the capacity between line and ground. If this capacity is evenly distributed, it is apparent that the potential to ground, $V_B$, will be distributed as in Fig. 6.

The voltage to ground at the middle of the exposure is zero at each end of the line it is $\frac{1}{2} E_B$.

If the control line is grounded at one end but open at the other, the $V_B$ of the grounded end is zero and the total voltage is thrown on the open end. (Fig. 7).

If the line is earthed at the center of the exposure, the same condition exists as in Fig. 6 and a protector at this location will do no good.

If the line is grounded at both ends, a short circuit is thrown on the induced e. m. f., $E_B$. A current will flow determined by the impedance of the circuit. Assuming zero ground resistance, the current is $\frac{E_B}{Z}$. Supervisory cables are usually made with No. 19 B&S gage wire, having a relatively high ohmic resistance of 44 ohms per mile; hence the reactance may be neglected and

$$I_B = \frac{e}{44} I_{fault}.$$

In this case the voltage to ground of the line is zero,

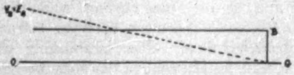

Fig. 7—Distribution of Potential on Line Grounded at One End

and therefore grounding the line at both ends of the exposure is the best safeguard against overvoltage. This can not be done actually, but can be accomplished in effect by connecting protectors between line and ground at or near the ends of the line. If the induced voltage is high enough to discharge the protectors—about 350—500 volts,—the line is effectively grounded for the duration of the fault on the transmission line. If the induction is not sufficient to break down the protectors, the potential on the line will distribute itself as in Fig. 1, but no damage will result. $V_B$ may be of the order of 500 volts. For this reason, a supervisory line should be treated as a 500-volt line.

The current which the protectors may be called upon to pass under fault conditions in the transmission line may reach high values, of the order of 50 amperes, under severe induction on open wire lines. The duration of the discharge may be as much as two seconds, which requires extremely sturdy arresters.

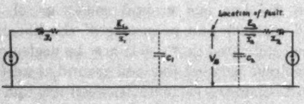

Fig. 8—Diagrams Showing Fault at Intermediate Point

In the foregoing, it is assumed that the fault in the transmission line is at one end of the exposure, so that the direction of the induced voltage is everywhere the same. Should the accidental ground on the power line occur anywhere between the ends—for instance—near the middle of the parallel, current will feed into the fault from both sides. These currents will be in opposite directions; hence the e. m. fs. induced in the sections of the control line on either side of the fault will be in opposition. The current which then flows in the control line ground loop when the protectors at the ends discharge will be a function of the resultant e. m. f. in the line. If the fault should occur midway between power sources of equal capacity, the resultant e. m. f. is zero and no current flows. This does not mean that no voltage to ground appears on the control line. The two induced e. m. fs. oppose each other and the line has distributed capacity to ground. Therefore, a voltage will pile up on the control line at a point opposite to the fault on the transmission line. This voltage may reach a considerable value, and if such is the case, a protector at or near that point is desirable. If a fault occurs somewhere within the parallel, the situation is as pictured in Fig. 8.

$Z_1$ and $Z_2$ are the impedances in the lines, $I_1$ and $I_2$ the currents, and $C_1$ and $C_2$ represent the distributed capacities. The voltage to ground, $V_B$ at the fault location will be $V = E_1 - I_1 Z_1 = E_2 + I_2 Z_2$, *i. e.*, somewhat less than the greater of the induced e. m. fs. but more than the smaller.

The voltage distribution will be as in Fig. 9.

$a$ = is the point opposite the fault in transmission line.

$a\,b = E_1$.

$b\,c = E_2$.

$a\,c = a'\,c' = E_1 - E_2 = I\,Z$ in the line.

When the protectors discharge there can be no potential to ground at $a'$, so the ground potential will take the position $o\,c'$. The voltage to ground at $a$ will then be $V = b\,d$. The ordinates between $o\,b$ and $o\,c'$ represent the distribution of the voltage to ground along one section; those between $b\,c'$ and $o\,c'$ that along the other.

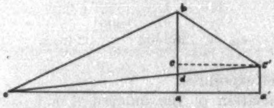

Fig. 9—Voltage Distribution with Fault as in Fig. 5

If there are no protectors on the line, or if they do not discharge, one-half the residual voltage,—that is, one-half the difference between $E_1$ and $E_2$—will appear at each end of the line and at the point corresponding to the fault on the transmission line.

Consideration of the case pictured in Fig. 9 shows that if the supervisory line is a cable, it may be well to install protection at intermediate points to safeguard the cable insulation or else use a more highly insulated cable. The number and location of protective equipments necessary to keep the induced voltage below hazardous values may be calculated from the characteristics of the transmission system and the control line. An open wire line will not require intermediate protection because the worst that can happen on the line is an insulator flashover which will probably not cause much damage.

The above discussion has dealt with a single-phase ground return power line, such as a railway trolley. On a three-phase system where the voltages are balanced, there will not be any magnetic field to speak of, and no induction is to be expected on the control line. If the voltages are unbalanced, unbalanced earth currents will flow and an e. m. f. will be electromagnetically induced on the control line.

In the case of a grounded neutral system with an accidental ground on one phase, a heavy ground current will flow. The ground current may be calculated and the induction derived by considering the disturbing line as a single wire with ground return.

Electromagnetic induction from ungrounded systems is usually not severe. So long as the voltage is balanced, no hazardous induction occurs. If an accidental ground occurs on one phase, the line currents will be unbalanced, a high voltage will appear between the ungrounded phases and ground, and a certain ground current will flow. This situation is discussed by Rudenberg (see bibliography) briefly as follows: At the point where the ground occurs, it may be assumed that the phase voltage is neutralized by a fictitious equal and opposite voltage, $-E\,p$, so that the voltage to ground at the fault is zero. This voltage, $-E\,p$, will cause currents to flow superimposed on the normal current caused by $E\,p$. The currents due to $+E\,p$ balance and do not disturb the control line. Then $-E\,p$ urges two currents to flow, one $i_1$ flowing around the loop consisting of phase 3 on the one hand and 1 and 2 in parallel on the other, and the capacity between them. These currents are indicated by the ordinates of the vertically hatched areas in Fig. 10, $i_1$ being balanced by $-i_1$ in 1 and 2 will cause no induction. The second current $i_2$ flows around the loop consisting of 3, the earth, and the capacity between 3 and the earth. It is a ground current and will induce an e. m. f. in the control line. The conditions are similar whether the fault occurs at the sending or the far end.

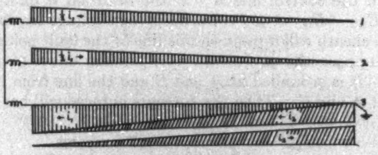

FIG. 10—CURRENTS DUE TO ACCIDENTAL GROUND ON ONE PHASE OF UNGROUNDED LINE

Some figures for the induction from ungrounded systems calculated by Eggeling (see bibliography) are given in Tables I and II. Table II is for simultaneous grounds occurring on two phases at opposite ends in which the ground current is a short circuit current and very heavy. The figures are taken from Eggeling's article and are for 50-cycle induction.

TABLE I

| $E_A$ kv. | $l$ | $c$ | $i$ | $E_B$ | $E_B$ in per cent of $E_A$ |
|---|---|---|---|---|---|
| 35 | 50 | 0.00443 | 2.10 | 64.2 volts | 0.18 |
| 35 | 50 | 0.00434 | 2.07 | 60.5 | 0.17 |
| 60 | 75 | 0.00433 | 5.30 | 230. | 0.32 |
| 100 | 100 | 0.00463 | 12.6 | 774. | 0.77 |
| 100 | 100 | 0.00475 | 12.9 | 755. | 0.76 |

TABLE II

| $E_A$ kv. | Plant kv-a. | $l$ | $i$ | $E_B$ | $E_B$ in per cent of $E_A$ |
|---|---|---|---|---|---|
| 35 | 20,000 | 50 km. | 540 | 16.5 kv. | 47 |
| 60 | 30,000 | 75 | 506 | 22 | 36.6 |
| 100 | 50,000 | 100 | 522 | 32 | 32 |

Here $l$ is the length of the parallel in kilometers, $E_A$ is the line voltage, $c$ is the capacity of the line to earth, $i$ is the disturbing ground current, *i. e.*, $\frac{1}{2}\,i_2$, $E_B$ is the e. m. f. induced in the disturbed line.

For lines with appreciable self-inductance in the path of the current $i_2$, and low ohmic resistance, resonant conditions may occur which may serve to raise the induction to values 3 to 4 times normal. The figures in the tables take no account of this, and may therefore be too low; on the other hand, mitigating circumstances are usually present, such as overhead ground wires or other grounded conductors; perhaps a cable sheath, which may considerably reduce the induction. In any event, it is apparent that the induction is heavy only for high line voltages and long exposures in such extreme cases as a double fault on two phases. On present-day supervisory control installations, the transmission line voltage and the length of exposure has been moderate. Ordinarily, therefore, the induction on supervisory cables used in conjunction with ungrounded systems will not be hazardous when the fault occurs on one phase only.

However, on systems with a grounded neutral, high voltages may be induced, as heavy fault currents will flow in the case of an accidental ground. As such systems are in the great majority in this country, and since it is difficult to lay down a general solution for the protective problem, each installation consisting of power and control line presenting an individual question, it may be well to work through a hypothetical case in order to clarify the matter. The calculations made will serve as an indication of what may be expected and as a guide to the methods to be applied in the investigation of actual installations.

With this in view, consider a system as depicted in Fig. 11.

In Fig. 11, $B$ and $C$ are two hydroelectric stations operated by supervisory control from a third station, $A$. These stations feed power into a system at 60 cycles through a 33,000-volt line, with the neutral grounded at each station. The generators and transformers at $A$, $B$, $C$ have reactances of 20 per cent and 10 per cent, respectively. The capacities of $A$, $B$, and $C$ are

15,000, 5000, and 6000 kv-a. The transmission line is No. 00 B&S gage copper with a triangular spacing of 36 in. *B* is 4 mi. from *A*, and *C* is 5 mi. from B. The supervisory line is a cable spaced 15 ft. from the transmission line. It consists of 10 pairs of No. 19 B&S wires running between *A* and *B* and 10 pairs from *A* to *C*. The cable between *A* and *B* thus contains 20 pairs of wires. At each end of each line, each conductor is connected to earth and cable sheath through a protector.

Then, from Fig. 5, $e = 0.51$ volts per ampere mile.

The problem thus resolves itself into a calculation of the ground current.

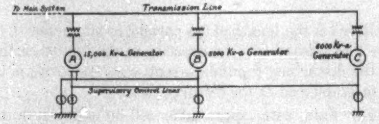

FIG. 11—EXAMPLE OF SYSTEM WITH SUPERVISORY CONTROL

Let us first assume the fault, a ground on one phase, to be at *C*, the end of the line. The calculations are easily made by the phase sequence method, following the procedure described by R. D. Evans (see bibliography). In the calculations made here, the effect of the connected system has been neglected in order to simplify the problem. This is a somewhat violent assumption as the system may feed a considerable amount of additional unbalanced ground current into the fault at *C*, unless the system is of small capacity. For an exact solution, the connected system should be taken into account and the induction will be higher than calculated here.

Applying the Evans method, the ground currents in the sections $B - C$ and $A - B$ are as follows:

$$I_{B-C} = 685 \text{ amperes.}$$

$$I_{A-B} = 382 \text{ amperes.}$$

These calculations neglect the effect of ground resistance which may or may not be a negligible factor, depending upon the individual system.

The induced e. m. fs. will be:

$$E_{AB} = 4 \times 382 \times 0.51 = 780 \text{ volts.}$$

$$E_{BC} = 5 \times 685 \times 0.51 = 1745 \text{ volts.}$$

Both in the same direction.

The voltage induced in the line $A - B$ is thus 780 volts; the voltage induced in the line $A - C$ is $780 + 1745 = 2525$ volts.

If the lines were totally isolated from ground and had no protection, the voltage to ground to which the insulation at the ends would be subjected would be:

$$V_{AB} = 390 \text{ r. m. s. or } 550 \text{ peak.}$$

$$V_{AC} = 1260 \text{ r. m. s. or } 1780 \text{ peak.}$$

When the protectors discharge current will flow around the loop $A - B$, and ground; and $A - C$ and ground.

These currents will be:

$$I_{AB}' = \frac{780}{4 \times 44} = 4 \text{ amperes,}$$

$$I_{AC}' = \frac{2525}{9 \times 44} = 6.4 \text{ amperes.}$$

Carrying the case further, let us assume the fault at *B*. We then find the ground currents in the transmission system to be:

$$I_{AB} = 750 \text{ amperes.}$$

$$I_{BC} = 408 \text{ amperes.}$$

These currents are in opposite directions. The induced e. m. fs. are:

$$E_{AB} = 1530 \text{ volts.} \qquad E_{BC} = 1040 \text{ volts.}$$

The line $A - B$ will have induced in it an e. m. f. of 1530 volts. If it were unprotected, a voltage of 765 r. m. s., or 1040 peak, would appear at each end between conductors and sheath.

In the control line $A - C$ the resultant e. m. f. will be $E_{AB} - E_{BC} = 490$ volts, but a high voltage to ground and sheath will appear on this line at the fault point, *C*.

Suppose the protectors have broken down so that $A - B$ is grounded at *A* and *B* and the line from *A* to *C* at *A* and *C*. Then the currents induced will be:

$$I_{AB}' = \frac{1530}{4 \times 44} = 8.7 \text{ amperes.}$$

$$I_{AC}' = \frac{490}{9 \times 44} = 1.2 \text{ amperes.}$$

Because of the fact that the e. m. fs. induced in $A - B$ and $B - C$ are in opposition, a voltage to ground will exist on the line $A - C$, with a maximum at *B*. This voltage is indicated by Fig. 12.

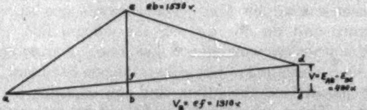

FIG. 12—VOLTAGES INDUCED IN CONTROL LINE SHOWN IN FIG. 11 WITH POWER-LINE FAULT AT B

The voltage at *B* is $ef = 1310$ volts.

Because the line $A - B$ has protection at *B*, its voltage to ground at *B* is zero and there may, therefore, be a potential of 1310 volts between the conductors of the line *A B* and those of the line $A - C$. This is a hazard. Consequently, in this case protectors should be installed on the line $A - C$ at or near *B*. The voltage $ef$ will then collapse. The protectors on $A - C$ at *B* will be called upon to discharge a current of

$$I_B' = \frac{1530}{4 \times 44} + \frac{1040}{5 \times 44} = 13.5 \text{ amperes.}$$

Now suppose the fault is at $M$, a point half-way between $A$ and $B$. The ground currents in the transmission system are then:

$$I_{AM} = 1095 \text{ amperes.}$$
$$I_{BM} = -690 \text{ amperes.}$$
$$I_{BC} = -316 \text{ amperes.}$$

The e. m. fs. induced in the control line are:

$$E_{AM} = 1120 \text{ volts.}$$
$$E_{BM} = -705 \text{ volts.}$$
$$E_{BC} = -805 \text{ volts.}$$

The resultant e. m. f. in the line $A - B$ will be 1120 $- 705 = 415$ volts in the direction $A$ to $B$, causing a current flow in the line $A - B$ of 2.4 ampere when the protectors discharge. If the voltage is of such a low order, the protectors may not discharge and the potential distribution will be as in Fig. 13. If they do discharge, the potential distribution will be as in Fig. 14.

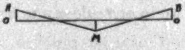

Fig. 13—Voltage on Control Line *A B* of Fig. 11 with no Protectors

$V_A = V_B = 208$ volts to ground. Power-line fault midway between *A* and *B*.

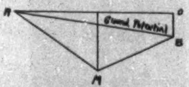

Fig. 14—Voltage on Control Line *A B* of Fig. 11, Protectors Discharging

Power-line fault midway between *A* and *B*.
$O M = -1120$ volts, $V_A = V_B = O$. $V_M = 900$ volts to ground.
Residual Voltage, $O B = 415$ volts.

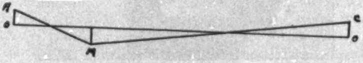

Fig. 15—Voltage on Control Line *A C* of Fig. 11 with no Protectors

Power-line fault midway between *A* and *B*.
$V_A = V_C = 195$ volts to ground.

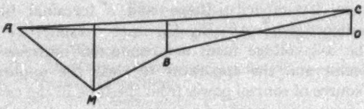

Fig. 16—Voltage on Control Line *A C* of Fig. 11, Protectors Discharging

Power-line fault midway between *A* and *B*.
$V_A = V_C = O$. $V_M = 1210$ volts. Residual voltage $= 390$ volts.

The resultant e. m. f. in the line $A - C$ will be $1120 - 805 - 705 = -390$ volts; that is, 390 volts in the direction $C$ to $A$. If there are no protectors on this line, the potential distribution will be as in Fig. 15. With protectors at $A$ and $C$, these will discharge and the distribution is as indicated in Fig. 16.

From these figures it is apparent that if protectors on both $A\,B$ and $A\,C$ discharge, there may exist appreciable differences of potential between the conductors of $A\,B$ and those of $A\,C$. This may be the cause of failure between conductors. To avoid this, protectors are necessary on $A\,C$ at $B$. If these are applied, there is no stress between conductors but only between the wires and sheath. Simultaneous protector operation probably does not always occur because if the protectors on one wire discharge, that wire becomes a grounded conductor and acts as a shield for the rest. On the other hand, the cable conductors are fairly high in resistance; hence their shielding action is probably small.

In the case of open wire lines, intermediate protection is not important. When cables are used, protection of cable insulation may be necessary to safeguard it from failure.

On open wire lines, the currents caused by the induction will be much heavier, because the wires used for open construction are much heavier and therefore less in resistance.

While the above described example may serve to indicate the nature of the induced voltages, much higher ones may exist particularly where large connected systems can feed into the ground fault, thus causing the flow of very heavy ground currents. For a system in which considerable energy may feed into the supervised section, all sources of current should be considered. Systems in which the induction may be high should be analyzed to determine the protector requirements if it is desired to safeguard the cable insulation against failures.

On the other hand, there are fortunately certain conditions which act to reduce the electromagnetically induced voltage so that the results obtained for the particular case calculated are possibly pessimistic. The proximity of grounded conductors exerts a shielding effect. The use of an overhead ground wire, or a neutral wire on the transmission line may reduce the induction considerably, since an appreciable part of the fault current will flow through this wire instead of through the earth, whereby the area of the disturbing loop and, therefore, the inducing flux are considerably decreased. The cable sheath itself, if well grounded, may be a potent reducer of induced e. m. f. The cable sheath acts as a short circuited damping turn. The degree of damping which it exerts depends upon the phase angle of the sheath. For effective shielding, it is important that the reactance of the sheath ground loop be as high as possible in comparison to its resistance which means that the sheath must be well grounded, and that the joints in it should be highly conducting. However, where the sheath resistance is appreciable, the shielding effect will be small. In the case of the 20-pair cable between *A* and *B*, in Fig. 13, the sheath resistance is 4.2 ohms per mile while the 60-cycle reactance is 1.2 ohms per mile. Hence, the phase angle and the shielding effect are quite small. For larger cables where the sheath resistance is lower, the shielding effect is much greater. Reductions of 30 per cent in induced voltage have been claimed for such cables. To obtain the best shielding effect, telephone cables have been constructed in which a shell consisting of a number of copper wires is located next to the lead sheath, these wires being solidly grounded at each end of the cable; also, with iron hoops around the sheath to increase the reactance. This has been done to reduce the electromagnetic disturbance of telephone communication. If shielding of this kind is resorted to, it is theoretically possible to forego entirely the use of protectors.

The ground connections to the protectors and the cable sheaths should be as low in resistance as possible. This is important to prevent the building up of high voltages across the ground resistance if heavy currents flow. A transient may be generated in the cable sheath either by lightning or induction from the transmission line. If this transient contains considerable energy, and if the ground resistances of the earth connections to the sheath are high, a high voltage drop may appear between the sheath and the ground. It is possible that this overvoltage may relieve itself from the cable sheath to the conductors of the supervisory line through the cable insulation and from there through the control apparatus to ground. Low ground resistance is important for all lightning arresters. The best lightning arresters hampered by high-resistance grounds, will not give good protection.

It is not to be recommended that cable sheaths be earthed to the station ground where the nature of the soil is such that a low ground resistance is not to be obtained. Under such conditions, if the station ground is used, and the ground fault occurs near one of the stations, a large part of the fault current will take the lower resistance path through the cable sheath in preference to the earth. Thus, the sheath may be called upon to carry very heavy currents which may be sufficient to damage the insulation because of heating, or even to injure the cable sheath. Where the ground resistances are high, the earth connections to the sheath and the protector should be made at a considerable distance from the station ground. As practically the entire voltage drop due to the ground resistance is concentrated within a comparatively short radius of the earth electrode, the cable will not pick up any great voltages if the sheath and station are well separated. The use of an overhead ground wire on the transmission line is of benefit in this connection as it will carry the greater part of the fault current.

A special protector has been developed for use on supervisory control circuits to relieve lightning voltages and with sufficient capacity to discharge the heavy currents of comparatively long duration which may be caused by induction. The essential element of this device is a spark-gap of particular design enclosed in an atmosphere of inert gas at a reduced pressure, to give a low breakdown voltage. The gas used permits of large energy discharges without undue injury to the electrodes which are of arc-resisting material. The breakdown voltage of the gap is of the order of 350 to 500 volts. The protector has four electrodes equally spaced from each other, so that several lines may be protected simultaneously. The most common practise is to connect two of the electrodes to earth, and each of the remaining two to one side of the line.

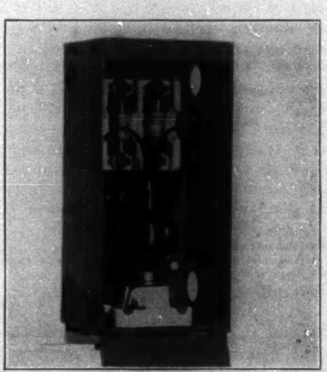

FIG. 17—SUPERVISORY-CONTROL PROTECTOR UNIT

The complete protector consists of the bulb herein described, mounted in a steel box with a pair of low-voltage, low-capacity fuses, and a terminal block. This device is shown by Fig. 17.

The low-voltage fuses are connected between the protector and the apparatus to clear the apparatus and source of control power from the tube in the case of a sustained discharge or a short circuit of the bulb in the extremity of a very heavy discharge. If the line is open wire, high-voltage fuses are connected between the line and protector to clear the line from the protector and apparatus in the event that it is crossed by the high-voltage wires. In that contingency, the protector discharges due to the line voltage and passes sufficient current to rupture the high-voltage fuses. This isolates the charged control line and prevents high voltage from appearing on the control apparatus. This is usual practise for open wire lines but not for cable.

Where the control line consists of a plurality of conductors, the required number of protective equipments is arranged in rows. The supervisory lines are run through the holes provided in the sides of the boxes and are tapped to the protectors. Each protector is separated from the next by the steel side of the cabinet so that a failure or possible arc in one box will not endanger the others.

The protector bulb is capable of discharging lightning voltages of any order except direct strokes nearby, and will handle many times discharges of 50 amperes of two seconds' duration. It will take care of heavier discharges, but at a sacrifice of length of life. It will discharge several hundred amperes, thereby keeping the voltage on the line below hazardous values even if it is destroyed by so doing.

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R. Rudenberg, "Elektrische Schaltvorgaenge."

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H. Pleijel, "Induction and Influence Disturbances in Parallel Conducting Systems," Published by A. B. Gunnar Tissells, Stockholm, Sweden.

R. D. Evans, "Finding Single-Phase Short-Circuit Currents," *Electrical World*, April 11, 1925, p. 760.

S. C. Bartholomew, "Power Circuit Interference with Telegraphs and Telephones," *Journal* of the I. E. E., Vol. 62 Oct. 1923, p. 817.

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## Discussion

**C. F. Publow:** These comments are contributed as a supplement to those given by:

1. H. C. Don Carlos under *Supervisory Systems*, see page 218, A. I. E. E. TRANSACTIONS, 1926,
2. Messrs. W. H. Gerrie and C. F. Publow under *Automatic and Supervisory Control*, see pages 1029-34, A. I. E. E. JOURNAL, October 1926, and as corrected in December 1926 A. I. E. E. JOURNAL,

which refer to the supervisory and Automatic installation of the Hydro-Electric Power Commission of Ontario.

Protection is always of vital importance and the following operating record will describe the functioning of the protective transformer equipment which the Commission designed and installed to overcome conditions outlined in the foregoing discussions which had made operation by supervisory control quite unsatisfactory.

The statement was made on page 1032 (see above) predicting the performance of the protective transformers as making the supervisory cable installation immune from:

1. Power lightning-arrester discharge.
2. An insulator spill-over at the control or either of the remote stations.

These protective transformers were installed in July 1926, thus giving up-to-date 1½ years of a service record which I believe is an enviable one. During this time, frequent electric storms have occurred over the district where the system transmission lines run and for this reason it seems safe to assume that the power arresters at all three points have discharged at least several times, and no troubles have been found in the cable.

As to insulator spill-overs at these stations, three have just recently occurred: twice at the control point where, due to ice conditions, an outdoor disconnecting switch, when being operated, flashed over to ground and possibly later developed a three-phase short circuit, the latter one being so severe and relatively long (5 or 6 sec.) that some of the generating stations went out of step; and the other occasion was an oil-switch bushing failure at one of the remote stations.

At the control station the outdoor switch in question had its base grounded to the power lightning-arrester ground located in the forebay a few feet from the substructure foundation. This ground is entirely separated from the station ground proper to which the supervisory equipment is grounded. They are, however, located only about 50 ft. apart, and thus in reference to the ground-voltage gradient which would occur, due to the flow of "fault" current, its effect on the telephone and supervisory cable would be approximately the same as if both grounds had been interconnected electrically. The system neutral is grounded at this station, as well as others, the ground being located approximately 800 ft. away from the station building and has a resistance of approximately 14 ohms. The resistance of the arrester ground is approximately 4 ohms as it forms about half of the total combined ground resistance at this station of approximately 2 ohms.

At the remote station, the oil breaker frame is grounded to the station ground of approximately 2 ohms resistance, it being the one to which the supervisory cable is also grounded.

*Connected Capacity.* The system had practically its total generated capacity in service at the time these "faults" occurred and it is estimated that a crest voltage of approximately 8000 volts to ground existed at the peak of the spill-overs.

*Condition of the Cable.* 1. After the first spill-over at the control point—on testing the cable after this "fault" occurred, it was found to be in exactly the same condition as on a previous test some months prior to this and practically the same as when the protecting transformers were installed.

2. After the oil breaker bushing failure at one of the remote stations, no test was made on the cable, but it is thought that one pair of wires failed at this time as described in (3).

3. After the second spill-over at the control station—on testing after this "fault," the two wires referred to in (2) were found short-circuited, one of which was a spare and therefore gave no indication on the equipment that there was cable trouble. However, it happened that one of our meter inspectors was listening in over a pair of wires in the supervisory control cable in connection with testing the remote metering at the time the "fault" occurred, and he reports there was no indication from the telephone of any system trouble. For this reason, the assumption made in (2) has been made.

Owing to the system not being normally connected when the spill-overs at the control point occurred, a number of breakers opened to clear the "fault" and split the system into several groups. Also on both occasions the "Bell" telephone connection (a lead-covered lead) to the control station was disabled and fuses were blown on the system telephone, thus rendering the station operator isolated temporarily from the dispatcher. On the latter occasion he knew from his supervisory indications the condition of the remote stations, and on his own initiative placed four of the six units in service within a few minutes after the "fault" occurred when they had all tripped off on "low" voltage, caused by the "fault," an operation expected by the operator: the other two machines apparently not pulling in due to the low voltage which was approximately 50 per cent normal before the four units were brought on, and about 90 per cent afterwards. This did not require even the replacing of a fuse, an important item under such circumstances.

This performance in a "pinch" is an exceptionally pleasing one from an operating standpoint, and one which is very gratifying to the Commission's engineers. It should be stated in this connection that this supervisory cable, prior to the installation of these protective transformers, suffered very severe damage on a number of occasions, some of them almost severing all the conductors and lead covering and examinations of short lengths of cable close to these damaged portions showed many burnt spots in the insulation of pin-hole size. The cable was only repaired at the time the protective transformers were installed, a number of the conductors was not clear, and thus owing to this condition, the faulty pair referred to in (2) and (3) above does not disturb our confidence in the protective transformers.

We believe Mr. Beck is familiar with the installation referred to, and it would be interesting to have him predict the functioning of the protective equipment described by him under such circumstances.

Mr. Beck refers to "low" and "high" ground resistances; I believe his paper would be more valuable if he were to definitely state the values of these ground resistances rather than use these relative terms.

**Chester Lichtenberg:** It very early developed that the standards of protection, maintenance, and operation of telephone and telegraph lines were not sufficiently high for supervisory purposes.

With supervisory systems, the lines are predicated to be in continuous service, even though no current may be carried over them. Therefore, if the lines are interrupted for any reason whatever, if they fail, if they are grounded, if they are burned off (as was the case in the experience of the Hydro-Electric Power Commission of Ontario), the entire supervisory system is rendered inoperative, and usually this condition occurs at a time of stress and when it is most needed. Consequently, too much stress cannot be laid upon the necessity for a high standard of maintenance and operation of lines used for supervisory systems.

**C. E. Stewart:** The paper by Mr. Beck gives a very clear and concise analysis of the abnormal potentials induced in line wires as ordinarily used for supervisory systems. Where the line wires parallel high-tension systems the protection problem must be treated in quite a different manner from that employed in telephone communication. In systems using d-c. impulses and holding or lockout circuits the connections must necessarily be metallic from the dispatcher's office equipment to the substation equipment. This prevents the use of the insulating transformer which is so commonly used as a protective device in wire telephony. It also means that the arrester, used possibly in connection with choke or retardation coils, must provide the entire protection against electromagnetic disturbances which, as the author points out, may under certain conditions be quite severe. Arresters used for supervisory equipment protection must be self-restoring, that is, they must be capable of discharging to ground without fusing or making a permanent connection as is the case of the carbon blocks used in telephone protective equipment.

That portion of the paper which deals with electromagnetic induction should be of special interest to operating companies, for this subject seems to be one which has been generally misunderstood.

One phase of the subject which is a bit outside the scope of this paper, but nevertheless associated and of interest, is the protection of line wires utilizing carrier current for the impulse channel. I refer to a wire circuit installed especially for the use of carrier-current supervisory equipment, such as that on the Chicago, South Shore, and South Bend Railroad. In this installation a wire was strung on the telephone crossarms. For a part of its 60-mile length, it is carried on the same poles as the 33,000-volt power circuits. The use of pellet-type arresters with high-voltage fuses at each of the eight stations has satisfactorily taken care of lightning, electromagnetic induction, and in one instance direct contact with the high-tension system.

The use of carrier current of course somewhat simplifies the protection problem and permits the use of very positive and reliable protective equipment. In this installation drainage coils eliminate static potentials.

**Caesar Antoniono:** Mr. Beck in his paper stated that if the control wires are in cable, then unless the lead sheath is fused by the short-circuit power current, high-voltage will be kept from the lines.

This is true, but it is also true that a grounded lead sheath is subject to severe burn-out in the case of power lines coming in contact with the lead sheath, and invariably the lines are damaged by the voltage carried through the cable to the nearest fusible cut-out, and sometimes pass that and damage the equipment, and the restoring of the lines is not a short job.

Another phase which I may touch on is the trouble with bullet holes. This is a trouble which it is difficult to locate and will introduce moisture in the cable lines and affect the control much more than the telephone.

I wish Mr. Beck would make more clear to me the paragraph in which he says, "Hazardous voltages of the order of hundreds of volts are the object of interest. It is therefore not necessary to be as particular in the assumption and calculation as would be the case were telephone or telegraph lines concerned in which very small disturbing voltages might cause false signals or interruption of the service."

If Mr. Beck has in mind that the supervisory control lines are not of equal importance with the telephone or telegraph lines, I must disagree with him, as we find where the control is employed, for switching purposes in particular, the service depending on this switching is affected by its failures. Therefore, our experience is that the lines used for supervisory control must be in better condition than for telephone use, where in carrying out a conversation over the telephone the missing of a word now and then is annoying but does not destroy the sense of the message. But in the case of supervisory control where selectors are used, a reduction of the impulse voltage may cause a failure of the switching contemplated, or an indication loss, or even a wrong switching may result.

In conclusion Mr. Beck covers in very fine style the theory of protecting the supervisory control lines but if these theories are applied in practise they are not going to work out in every detail as given. The highest degree of service can be obtained from the supervisory control lines and system. But we have not yet a control that is nearly 100 per cent reliable when it is most needed. In our experience although we have had various protective devices on our supervisory lines, we have experienced trouble and often the control system has been out of commission at times of power-system trouble when it was most needed.

Summing it up, it seems to me that after having done what Mr. Beck recommends, there is still a desire for improvement in making the supervisory control system trouble-proof against these conditions so as to obtain 100 per cent service during emergencies. Protecting the lines is a step in the right direction, but any disturbance at this time, even the blowing of a fuse during emergencies, can impair and cause inconvenience in the service rendered.

**Alfred Herz:** (by letter) Mr. Beck's paper draws attention to a condition inherent with physically parallel wire systems and which is very often overlooked. True enough, similar conditions have been thoroughly investigated and experimented upon mostly in the cases of telephone systems physically paralleling power lines. The forces causing the effect are known, precautions and mitigating measures are also known and resorted to in this (telephone) practise.

Committees of engineers have carried on the experiments mutually and satisfactory coordination has been accomplished. The foremost body to work on this coordination is, without doubt, the Inductive Coordination Committee of the National Electric Light Association. I am citing the above just to bring before you the fact that this inductive effect is nothing new and nothing peculiar to supervisory control lines, but is liable to be encountered on pilot-wire relay systems and elsewhere.

To cite an example which came to my attention: The power system involved consisted of single-conductor cables (3-phase) located underground and in parallel ducts to the pilot-wire system which was grounded at both ends. Causes of trouble on the power system beyond the zone protected by the pilot wires promptly caused the pilot-wire relay system to operate at the wrong time. In tracing the matter down we found that extraordinary precautions had been taken to keep the pilot wire at ground potential; this was accomplished by grounding both ends of the system.

When single-phase trouble occurred beyond the protected zone, currents were induced in the pilot wire which were not entirely balanced in the return wire provided, part of the induced current returning through the earth. In this particular case satisfactory operation was obtained by eliminating the ground connection at one end of the pilot system and providing at this point a low-voltage lightning arrester, similar to the one mentioned in Mr. Beck's paper, to guard against the induced voltage at the time of trouble causing insulation breakdown.

From my work with the N. E. L. A. Inductive Coordination Committee I know that in many cases more attention should be paid to the comparatively simple remedial or preventative measures which can often be resorted to more effectively when the installation is being made than afterwards.

**Edward Beck:** Mr. Publow's discussion is of particular interest in so far as it describes an additional method of cable protection where grounding conditions are troublesome. In my opinion, the same degree of protection would be secured by the use of the arresters described in the paper, provided the cable-sheath ground is well separated from the neutral ground so that fault current is kept out of the cable sheath. It would be interesting to know the resistance of the ground path, including the electrodes, between the stations described by Mr. Publow.

The question of what is a low and what is a high ground resistance always arouses considerable discussion. For lightning arresters on power circuits, a figure of 15 ohms has been mentioned now and again as a maximum. A 15-ohm ground for a distribution type of arrester is probably satisfactory although a lower resistance is better. For the ground-to-cable sheaths and supervisory control protector equipment, the ground resistance should be of the same order. Station and neutral grounds should be as low as possible, of the order of a very few ohms if possible.

Referring to Mr. Antoniono's discussion, possibly I did not express myself very clearly in the paper when speaking of the order of voltages in which we are interested. For the protection of these lines, we should like to know whether the voltages which may be induced between line and ground are a few volts or many. The voltages which are induced between wires are of no particular consequence in this case, but they are in telephone practise. In order to calculate these voltages between wires which give rise to interference, it is necessary to be more exact in the calculations than in the case of supervisory control lines where they are not likely to be high enough to cause trouble. It is quite true that supervisory control lines are as important as telephone lines, perhaps more so, as Mr. Lichtenberg has pointed out, but the possibility of interference with the control is more likely to be an apparatus failure than interference with signals due to disturbing voltage between wires.

With careful protection as outlined in the paper, much can be done toward making the supervisory immune to failures from overvoltage. It is difficult to make general recommendations which will cover all conditions. There are always exceptions and nearly all installations require individual study to achieve the best results. Considerable good can be done by scrutiny of the problem before the installation is made and by installing the lines with the conclusions of this study in mind. Perfection has not been attained. We hope it never will be as it would put a stop to progress. But we are of the opinion that better means of protecting supervisory control systems are available now than formerly, and that by careful application, control failures may be reduced to a minimum.

# 1926 Lightning Experience on 132-Kv. Transmission Lines

BY PHILIP SPORN[1]

Member, A. I. E. E.

***Synopsis.***—*This paper deals with the interruptions due to lightning on an extensive interconnected 132-kv. system during the year 1926, a similar record covering part of the system having been reported previously.*[2] *A layout of the system is shown and details of the type of line and tower construction are given in considerable detail.*

*The lightning performance of different sections of the line have been reduced to a common basis and discussed from the point of view material of line structure, height of line, ground wire, and line protective equipment.*

*Changes in tower design are discussed in the light of experience gained in the past. The work done the past year to reduce the lightning troubles at the stations is described.*

*The efficacy of the ground wire seems very definitely shown but it is believed further study and attention should be given this matter as a means of reducing the lightning voltage on transmission lines, particularly to reducing the lightning voltage at and near a switching station.*

*The problem of determining the damage to line conductors, etc., is an important one. Data on this are at present incomplete, but it is planned to obtain a systematic record in the future which will, it is believed, supply valuable design information.*

## INTRODUCTION

IN the spring of 1926 there was presented before the Institute a paper[2] on the performance of a number of 132-kv. steel tower lines on the system of the American Gas and Electric Company which covered in detail the performance and experience with these lines during the year 1925. Further performance data were promised in that paper, but it has not been found easy to carry out this promise, made with the very best of intentions. In the first place, the lines and system of which these data are a part, have not been operating as a unified system for a very long period. Secondly, the operating personnel has at no time been particularly large. In other words, it has always been down to a strict operating basis. Third, when a line goes out of service, it is undoubtedly the business of the operating man to get it into service with as little delay as possible and afterwards try and determine, if possible, what has happened. When the excitement of the emergency has passed, this often results in a lack of evidence that will withstand critical analysis or give any real information as to what has happened such as would be of real benefit to future design. That there can be worked out an operating set-up which would not overburden the system and yet make it possible to obtain all information necessary, there can be no reason to doubt; but it takes time to work out such a set-up and with the system under discussion that time has been very short. Keeping this in mind it is easier to understand why some of the records presented are in some respects incomplete. They are, however, the best records that could be obtained and perhaps that could be expected.

## GENERAL

Fig. 1 shows the 132-kv. transmission network in question. It comprises approximately 910 mi. of actual line, about one-third of which is double-circuit, the actual circuit miles being approximately 1245. The major portion of this network was placed in operation very late in 1925, in 1926, or early in 1927; and one portion, (namely, the Switchback-Logan line), has not yet been placed in operation at the time of writing (November 1927) although it is expected that it will be in operation by the end of 1927.

The nature of the terrain which this network traverses is most varied, ranging from the extremely flat lands in Indiana to the heavy mountainous country in West Virginia.

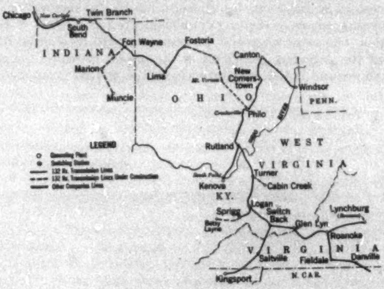

FIG. 1

The system is fed by large generating stations at Twin Branch, Philo, Windsor, Kenova, Cabin Creek, Logan and Glen Lyn. It is tied in with the Chicago system and the systems of the West Penn Power Company, The Ohio River Edison Company, The Ohio Public Service Company, and the Cleveland Electric

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[1] Electrical Engr., Am. Gas & Electric Co., New York, N. Y.

[2] *Lightning and Other Experience with 132-Kv. Steel Tower Transmission Lines*, Sindeband and Sporn, A. I. E. E. TRANS., Vol. 45, p. 770.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Feb. 13-18, 1928.*

TABLE I

CHARACTERISTICS OF 132-KV. LINES—AMERICAN GAS AND ELECTRIC COMPANY

| Column No. 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Line designation | Glen Lyn<br>Roanoke | Glen Lyn<br>Switch-back | Lima<br>Fostoria | Lima<br>Tw. Branch | Logan<br>Sprigg | Philo<br>Canton | Philo<br>Crooksville | Philo<br>Turner | Roanoke<br>Danville | Roanoke<br>Reusens | Rutland<br>So. Point | Saltville<br>Kingsport | Switchback<br>Logan | Switchback<br>Saltville | Turner<br>Logan | Tw. Branch<br>So. Bend | Windsor<br>Canton | So. Bend<br>New Carlisle |
| Initially placed in service | 6/13/26 | 8/13/27 | 9/3/25(e) | 9/18/25 | 6/28/26 | 9/28/24 | 9/28/24 | 4/22/26 | 9/16/26 | 5/5/26 | 3/15/26 | 8/25/27 | 11/27/27 | 10/16/27 | 1/30/26 | 4/5/25 | 9/–/17 | 6/24/26 |
| Length of line—(Miles) | 65.0 | 30.0 | 45.6 | 128.5 | 21.0 | 73. | 15.4 | 118.7 | 65.0 | 43.0 | 50.3 | 56.0 | 50.0 | 46.0 | 40.2 | 4.9 | 55.0 | 17.7 |
| Number of circuits | 2 | 2 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 2 | 2 | 1 |
| Size of conductor wire—(C. M.) A. C. S. R. | 397,500 | 397,500 | 336,400 | 397,500 | 4/0 | 336,400 | 336,400 | 397,500 | 336,400 | 397,500 | 397,500 | 397,500 | 397,500 | 397,500 | 336,400 | 397,500 | 200,000(a) | 397,500 |
| Number of ground wires | 1 | 1 | 1 | 1 | None | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | None | 1 | 2 | 1 |
| Size of ground wire—(C. M.) A. C. S. R. | 397,500 | 397,500 | 159,000 | 159,000 | None | 159,000 | 159,000 | 159,000 | 159,000 | 197,500 | 159,000 | 159,000 | 397,500 | 159,000 | None | 159,000 | 159,000 | 159.000 |
| Date ground wire installed | 6/13/26 | 8/13/27 | 5/15/26 | 6/7/26 | None | 5/6/26 | 4/9/26 | 4/22/26 | 9/16/26 | 5/5/26 | 3/15/26 | 8/25/27 | .. | 10/16/27 | None | 6/8/26 | 9/–/17 | 6/24/26 |
| Line configuration—(Horizontal-Vertical) | V | V | V | V | H | V | V | V | V | V | V | V | V | V | V | V | V | V |
| Protection—Rings and horns | No | Yes | No | Yes | No | Yes | No | No | No | Yes | No | Yes | Yes | Yes | Yes | Yes | No | No |
| Protection—Horns line side | Some | .. | Some | .. | .. | .. | .. | Yes | Some | .. | .. | .. | .. | .. | .. | .. | Some | Some |
| Protection—Horns ground side | Some | Yes | Some | Yes | .. | Yes | .. | .. | Some | Yes | .. | Yes | Yes | Yes | Yes | Yes | Few | Some |
| Nature of terrain | Rolling to mountainous | Very mountainous | Very flat | Very flat | Very mountainous | Rolling | Rolling | Rolling to mountainous | Rolling | Rolling | Rolling | Rolling to mountainous | Very mountainous | Mountainous | Very mountainous | Very flat | Rolling | Flat |
| Length per insulator—(Inches) | 4–3/4 | 5–1/8 | 4–3/4 | 5–3/4 | 6–7/16 | 4–3/4 | 4–3/4 | 4–3/4 | 5–1/8 | 5&4–3/4 | 4–3/4 | 5–1/8 | 5–1/8 | 5–1/8 | 5&4–3/4 | 5–3/4 | 4–3/4 | 5–3/4 |
| Insulators per string (Suspension) Top | 11 | 11 | 12 | 10 | 10(b) | 11 | 12 | 12 | 11 | 12 | 12 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| Middle | 11 | 11 | 12 | 10 | 10×10M | 11 | 12 | 12 | 11 | 12 | 12 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| Bottom | 10 | 10 | 10 | 9 | 10(b) | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 9 | 10 | 9 |
| Length of susp. ins. string (Inches) Top | 52.25 | 56.38 | 57.0 | 57.5 | 64.4 | 52.25 | 57.0 | 57.0 | 56.38 | 57.0 | 57.0 | 51.3 | 51.3 | 51.3 | 47.5 | 57.5 | 47.5 | 57.5 |
| Middle | 52.25 | 56.38 | 57.0 | 57.5 | 64.4 | 52.25 | 57.0 | 57.0 | 56.38 | 57.0 | 57.0 | 51.3 | 51.3 | 51.3 | 47.5 | 57.5 | 47.5 | 57.5 |
| Bottom | 47.50 | 51.3 | 47.5 | 51.75 | 64.4 | 47.50 | 47.5 | 47.5 | 51.3 | 47.5 | 47.5 | 51.3 | 51.3 | 51.3 | 47.5 | 51.75 | 47.5 | 51.75 |
| Dead ends—(Single or double) | D | D | D | D | D | D | D | D | D | D | D | D | D | D | D | D | D | D |
| Insulators per string (Dead end) Top | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 11 |
| Middle | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 11 |
| Bottom | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 11 |
| Type towers | A-B-C-E | G-H-K-E | A-B-C | A-B-C | Wd. pole (c) | A-B-C | A-B-C | A-B-C-E | A-B-M-P | A-B-C | A-B-C | AA-BB-CC-E | G-H-K-E | AA-BB-CC-E | B-C-E | A-B-C | Ao-Bo | A-B-C-G |
| Total number of towers | 269 |  | 215 | 603 | 189 | 298 | 69 | 425 |  | 199 | 191 |  |  |  | 155 | 24 | 487 | 82 |
| Number of towers with 10′ extension | 35 |  | 78 | 188 | .. | 71 | 13 | 67 |  | 19 | 26 |  |  |  | 2 | 5 | 101 | 23 |
| Number of towers with 20′ extension | 55 |  | 48 | 166 | .. | 48 | 12 | 51 |  | 39 | 38 |  |  |  | 4 | 7 | 23 | 19 |
| Number of towers with 30′ extension | .. |  | .. | 2 | .. | 1 | .. | .. |  | 0 | 2 |  |  |  | 0 | .. | .. | 2 |
| Number of towers with 40′ extension | .. |  | .. | .. | .. | .. | .. | .. |  | 0 | .. |  |  |  | 4 | .. | 2–50′ | .. |

(a) Copper conductor
(b) Sides—some with 9 insulators
(c) With steel crossarms
(d) On "E" Towers
(e) Operated 8/3/24 to 9/3/25 @ 66 kv.
(f) Side cond. to pole
(g) Center to outside conductor
(h) To wood pole. 4.0′ deg. to crossarm
(x) "E" Towers

TABLE I—*Continued*

CHARACTERISTICS OF 132-KV. LINES—AMERICAN GAS AND ELECTRIC COMPANY

| Column No. 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Line designation | Glen Lyn<br>Roanoke | Glen Lyn<br>Switch-back | Lima<br>Fostoria | Lima<br>Tw. Branch | Logan<br>Sprigg | Philo<br>Canton | Philo<br>Crooks-ville | Philo<br>Turner | Roanoke<br>Danville | Roanoke<br>Reusens | Rutland<br>So. Point | Salt-ville<br>Kings-port | Switch-back<br>Logan | Switch-back<br>Salt-ville | Turner<br>Logan | Tw. Branch<br>So. Bend | Windsor<br>Canton | So. Bend<br>New Carlisle |
| Average length of span—(Feet) | 1270 |  | 1102 | 1125 | 585 | 1295 | 1160 | 1470 |  | 1140 | 1376 |  |  |  | 1360 | 1016 | 595 | 1125 |
| Maxmium length of span—(Feet) | 3321 |  | 1400 | 1775 | 2220 | 2665 | 2200 | 3050 |  | 2135 | 2858 |  |  |  | 3770 | 1375 | 1550 | 1876 |
| Minimum length of span—(Feet) | 100 |  | 745 | 610 | 85 | 360 | 480 | 410 |  | 434 | 465 |  |  |  | 280 | 520 | 150 | 156 |
| Height of std. tower (Gr. to top crossarm (Ft.) | 90 | 92 | 90 | 90 | 35–40 | 90 | 90 | 90 | 92 | 90 | 90 | 90½ | 92 | 90½ | 90–45(x) | 90 | 74 | 90 |
| Conductor spacing (vertical) (Ft.) Top—Mid | 13 | 15 | 13 | 13 | .. | 13 | 13 | 13 | 15 | 13 | 13 | 13½ | 15 | 13½ | 13 | 13 | 12 | 13 |
| Mid.—Bot | 13 | 15 | 13 | 13 | .. | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 12 | 13 |
| Conductor spacing—(Horizontal) (Ft.) Top (For standard towers) | 21.75–23<br>21.75(d) | 26.75–28<br>21.75(d) | 26.75–23 | 26.75–23 | 15.0(g) | 26.75–23 | 26.75–23 | 26.75–23<br>21.75(d) | 26.75–28 | 21.75–23 | 21.75–23 | 24.75–26<br>21.75(d) | 26.75–28 | 24.75–26 | 23<br>21.75(d) | 26.75–23 | 21.75 | 26.75–23 |
| Middle | 26.75–28<br>21.75(d) | 31.75–33<br>21.75(d) | 26.75–28 | 26.75–28 | .. | 26.75–28 | 26.75–28 | 26.75–28<br>21.75(d) | 31.75–33 | 26.75–28 | 26.75–28 | 29.75–31<br>21.75(d) | 31.75–33 | 29.75–31 | 28<br>21.75(d) | 26.75–28 | 31.75 | 26.75–28 |
| Bottcm | 21.75–23 | 26.75–28 | 21.75–23 | 21.75–23 | .. | 21.75–23 | 21.75–23 | 21.75–23 | 26.75–28 | 21.75–23 | 21.75–23 | 24.75–26 | 26.75–28 | 24.75–26 | 23 | 21.75–23 | 21.75 | 21.75–23 |
| Clearance—Line to tower (Normal pos.) Top At suspension strings–(Ft). | 6.0 | 6.5 | 5.75 | 5.75 | 7.0(f) | 6.0 | 5.75 | 5.75 | 5.0 | 5.75 | 5.75 | 5.0 | 7.0 | 5.0 | 5.0 | 5.75 | 5.25 | 5.75 |
| Middle | 6.5 | 6.5 | 6.25 | 6.25 | 5.0 | 6.5 | 6.25 | 6.25 | 6.5 | 6.25 | 6.25 | 6.75 | 7.0 | 6.75 | 7.25 | 6.25 | 9.0 | 6.25 |
| Bottom | 7.5 | 10.0 | 7.5 | 7.5 | 7.0(f) | 7.5 | 7.5 | 7.5 | 9.75 | 7.5 | 7.5 | 9.0 | 10.0 | 9.0 | 7.5 | 7.5 | 7.75 | 7.5 |
| Clearance—Line to tower—(45 deg. Pos.) Top At suspension strings–(Feet) | 4.8 | 5.0 | 5.0 | 5.0 | 3.25(h) | 4.8 | 5.0 | 5.0 | 4.8 | 5.0 | 5.0 | 4.0 | 4.0 | 4.0 | 3.75 | 5.0 | 3.25 | 5.0 |
| Middle | 4.8 | 5.0 | 5.0 | 5.0 | .. | 4.8 | 5.0 | 5.0 | 4.8 | 5.0 | 5.0 | 4.0 | 4.0 | 4.0 | 3.75 | 5.0 | 3.25 | 5.0 |
| Bottom | 3.75 | 4.0 | 3.75 | 3.75 | 3.25(h) | 3.75 | 3.75 | 3.75 | 4.0 | 3.75 | 3.75 | 4.0 | 4.0 | 4.0 | 3.75 | 3.75 | 3.25 | 3.75 |

(a) Copper conductor
(b) Sides—some with 9 insulators
(c) With steel crossarms
(d) On "E" Towers
(e) Operated 8/3/24 to 9/3/25 @ 66 kv.
(f) Side cond. to pole
(g) Center to outside conductor
(h) To wood pole. 4.0 deg. to crossarm
(x) "E" Towers

TABLE II

OPERATING RECORD OF 132-KV. LINES—AMERICAN GAS AND ELECTRIC COMPANY

| Column No. 1 | 2 | 3 | 4 | 5 | 6 | 7 |  | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Line designation | Glen Lyn<br>Roa-noke | Glen Lyn<br>Switch-back | Lima<br>Fos-toria | Lima<br>Tw. Branch | Logan<br>Sprigg | Philo<br>Canton |  | Philo<br>Crooks-ville | Philo<br>Turner | Roa-noke<br>Dan-ville | Roa-noke<br>Reusens | Rut-land<br>So. Point | Salt-ville<br>Kings-port | Switch-back<br>Logan | Switch-back<br>Salt-ville | Turner<br>Logan | Tw. Branch<br>So. Bend | Wind-sor<br>Canton | So. Bend New<br>Car-lisle |
|  |  |  |  |  |  | 1925 | 1926 |  |  |  |  |  |  |  |  |  |  |  |  |
| Outages (One circuit only) Due to lightning—1926 | 16 | .. | 9 | 23 | 3 |  | 13 | 3 | 11 | 0 | 13 | 3 | .. | .. | .. | 16 | 0 | 9 | 0† |
| Circuit outages due to lightning—1926 | 20 | .. | 9 | 23 | 3 | 88 | 15 | 3 | 11 | 0 | 13 | 3 | .. | .. | .. | 18 | 0 | 11 | 0† |
| Circuit outages per 100 mi. of line per yr.—1926 | 48* | .. | 19.8 | 17.9 | 31* | 120 | 20.5 | 19.5 | 10.6* | 0 | 36.6* | 6.3* | .. | .. | .. | 44.8 | 0 | 20 | 0† |
| Circuit outages per 100 mi. of circuit per yr.—1926 | 24* | .. | 19.8 | 17.9 | 31* | 60 | 10.3 | 19.5 | 10.6* | 0 | 36.6* | 6.3* | .. | .. | .. | 22.4 | 0 | 10 | 0† |

*Corrected for one calendar year on basis of Fig. 3.
†Record incomplete.

Illuminating Company at 132,000 volts. The short-circuit capacity on the system varies from approximately 1750 amperes to approximately 4750 amperes, at 132,000 volts. Values as high as 4000 amperes have been actually measured.[3] From a lightning standpoint, the network as a whole is subjected to thunderstorms considerably in excess of the average over the country as a whole. The isoceraunic lines, *i. e.*, lines connecting points of equal thunderstorm intensity, for the territory in question ranged from 40 to 60 in April, 150 to 200 in June and July, and down to about 60 to 80 in September. All these figures are based on a 20-year period. The average number of storms for the territory as a whole, based on the 20-year data, referred to above, is given in Fig. 2.

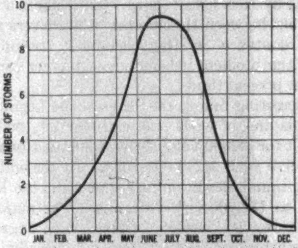

Fig. 2—Average Monthly Distribution of Thunderstorms

In N. Indiana, Ohio, Va., W. Va. and E. Kentucky, based on 20-year average (1904-23)

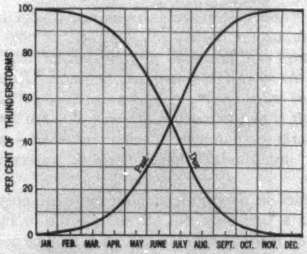

Fig. 3—Per Cent of Thunderstorms During One Year

In N. Indiana, Ohio, Va., W. Va. and Kentucky, based on 20-year average (1904-23)

## Description of Lines and 1926 Performance

In Table I there is given a description of the physical characteristics of the various portions of the 132-kv. network under discussion.

The towers referred to in the above table are types A, B, C, A A, B B, C C, E, G, H, K, M, P, $A_0$, $B_0$. Towers A, B, C and Towers G, H, and K, have already been described elsewhere.[2] Tower E is a single-circuit tower with conductors arranged in a horizontal plane and utilized especially on long span work. Towers M and P have in general the same dimensions and spacings as towers G and K, with the exception of different factors of safety for the various loadings being employed. Towers A A, B B, and C C, which have been utilized on the very recently constructed lines, are very similar to types A, B, and C, although the tower is quite definitely designed for equal string length on all three phases, this being made possible by the use of the ground wire; and further, clearances are better balanced with respect to lightning voltage. The tower further differs from the previous types in that in its design definite provision has been made for the addition of a second ground wire if operating experience should prove that this is desirable. A sketch of the type A A tower is shown in Fig. 4.

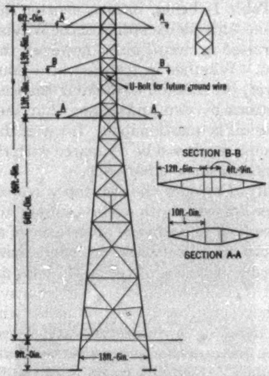

Fig. 4

The performance of the lines during 1926, is shown in Table II. It will be noted that although some of the lines had been in service for only a portion of the year 1926, for comparison purposes, the number of outages has been converted to a yearly basis by the use of Fig. 3. Fig. 3 is merely an integration of the thunderstorm distribution curve shown in Fig. 2.

Examining Table II further, it will be noted, first, that the largest number of lightning outages occurred on the Twin Branch-Lima line. This line was in service for the full year, and has a length of 128½ mi. Based on 100 mi. of circuit, however, it is not at all out of line and checks up with similar performance on the Lima-Fostoria line, and on the Philo-Crooksville line. On the basis of 100 line mi. the largest number of interruptions occurred on the Glen-Lyn-Roanoke line, but this figure is of course subject to the weakness that the line was in service for 6 months only, and there is no way of checking up whether the ratio employed for figuring the yearly number of interruptions was correct for the entire year.

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[3] *Tests on High- and Low-Voltage Oil Circuit Breakers*, Sporn and St. Clair, Trans., A. I. E. E., Vol. XLVI, 1927, p. 289.

[2] Loc. cit.

[4] See *Monthly Weather Review*, Vol. 52, No. 7, July 1924.

Of the lines that were in service for an entire year the largest number of interruptions per 100 mi. of line was sustained by the Logan-Turner line. This is a line that has no ground wires and, in addition, passes through especially rugged country. The length of the insulator string on this line is particularly short (as shown in Table I) being, in fact, shorter than that of any other line with the exception of the Windsor-Canton line. Expressed in circuit miles, however, the record is rather good. Whether in the case of a double-circuit line, however, the method of dividing the total number of interruptions by two and calling that the interruptions per circuit is questionable. It raises the question whether such a result can be compared with the number of flashovers on a single-circuit line.

To amplify: Consider the two top wires of a double circuit tower line with both circuits subject to the same potential gradient. Upon the occurrence of a lightning discharge, chance will usually determine which one of the two circuits is to flash over first. This assumes, of course, that their arrangement is perfectly symmetrical and that they constitute the same phase wire in their respective circuits. A flashover having occurred on one of them, the question arises whether that flashover does not reduce the energy in the surge sufficiently to lower the head of the wave to such an extent that the second wire will not flash over. The fact that among all the double-circuit lines the maximum number of instances in which both circuits flashed over on any one line was only four against a total number of flashovers of 20 would certainly tend to indicate that some such explanation may be the correct one.

The Roanoke-Reusens line is third in the number of interruptions per 100 mi. of line, but the figure for a whole year was again obtained by a ratio and is open to the same objections as the figures for the Glen Lyn-Roanoke lines. The Philo-Canton and the Windsor-Canton lines, in spite of the fact that the Philo-Canton line generally is exposed to more severe storms than the Windsor-Canton line, have practically the same record for the year 1926, when reduced to a 100-mi. basis. One of these lines, namely the Windsor-Canton line, has two ground wires and is considerably lower than the Philo-Canton line which has only one ground wire. The record during 1926 would seem to show that, from the standpoint of reliability the Philo-Canton line, even though it has only one ground wire, has been put on a plane of reliability equal to that of the Windsor-Canton line. From the data gathered on the Glen-Lyn-Reusens line and Roanoke-Reusens line in 1926, it would seem that the ground wire on these lines was not so effective as it was on the other lines. The ground wire construction being in general the same on all of the lines, a possible explanation for the large number of flashovers may lie in the fact that the tower resistance over the lines as a whole is rather high. Some of the operating data cited by Hemstreet[5] showed that there is a definite relationship between the number of flashovers and the ground resistance in the particular section. This phase of the problem is being given further consideration at the present time.

An interesting line in the series is the Logan-Sprigg line. This line, of wood pole construction, was originally built for 88,000 volts and was operated for a period of about five years at 44,000 volts. At the end of this time, additional insulation was added and the line was cut over to 132,000-volt operation. The majority of the structures are 2-pole A frames with ungrounded steel crossarms. The insulation is unusually liberal. For a while, when the line was first placed in operation, the operating records seemed to indicate an almost lightning-proof line, but detailed investigation has shown that this was not quite so. Considering the shortness of the line,—namely 21 miles,—the record is not particularly good although again the record is open to the criticism that a full year's data were not available.

The rest of the data requires no particular comment.

## PERFORMANCE OF PROTECTIVE DEVICES DAMAGE TO CONDUCTORS, INSULATORS, AND HARDWARE

The records of damage to insulators, conductors, and hardware, on the lines is not complete for 1926 so that no attempt will be made to give specific data in this paper. As already pointed out, 8 out of 17 lines now in service were placed in operation during 1926 with the result that the method of inspecting the lines and the reports of damages thereon have not been sufficiently organized to make these data accurate for analysis.

The fact is outstanding, however, that only in one case has a line been out of service due to lightning trouble on it for a period in excess of the time necessary to close the line back in service. The one case referred to occurred on May 18 on the Windsor-Canton line where both circuits tripped automatically due to the breaking of two line wires. It is interesting to note that this occurred on a line that had been very conservatively designed from the standpoint of height above ground, but on the other hand, it had practically no arcing protection. This again substantiates the point that in designing a line both preventive and remedial measures must be considered. Lowering a line, for example, will undoubtedly reduce the lightning voltage which may be induced on the line. Installing a ground wire will do the same thing. Both these measures are preventive. The purpose of the arcing protective devices on the other hand are decidedly remedial.

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[5] *Recent Investigation of Transmission Line Operation*, J. G. Hemstreet, TRANS., A. I. E. E., Vol. XLVI, 1927, p. 835.

Other cases of trouble, such as burned conductors, burned hardware, and ground wire,—also broken porcelain—were found in moderate amounts by normal patrol and repaired at prearranged times without interruption to normal service. This indicates that from an operating point of view, conditions were very much better than during 1925 on the Philo-Canton line. As typical of the action of the arc on a 132-kv. insulator string with and without arcing protective devices, Figs. 5, 6, and 7 are shown. Fig. 5 illustrates the effect of a heavy arc on a string without protective devices; Fig. 6 shows the action of a less heavy arc on a similar string. In the original photograph, the burns on the top unit are very clearly noticeable. Fig. 7 shows the action of an arc on another string equipped with rings and horns. The effect of the arc on the rings and horns is very clear in the photograph.

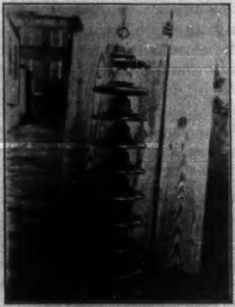

FIG. 5—RESULT OF TYPICAL FLASHOVER OF 132-KV. INSULATOR STRING WITHOUT ARCING PROTECTION

(Note badly shattered insulator on ground side)

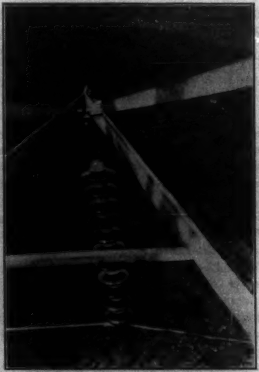

FIG. 6—RESULT OF TYPICAL FLASHOVER OF 132-KV. INSULATOR STRING WITHOUT ARCING PROTECTION

(Note top insulator still intact but badly burned)

### DESIGN DEVELOPMENTS DURING 1927

The experience gained during 1926 was naturally incorporated in some of the design work carried on during 1927 and particularly along the following lines:

1. Whereas in 1926 an extensive program of ground wire installation was carried out, in 1927 much more attention than in the past was given to a phase that had been apparently neglected, and that was the problem of the line entrance. In every case, the ground wire was brought into the station structure and where the station structure design allowed, the number of ground wires brought into the station structure was made larger than the number on the line itself, all with the idea of reducing as much as possible the surge impedance of that portion of the system running from the last tower to the bus.

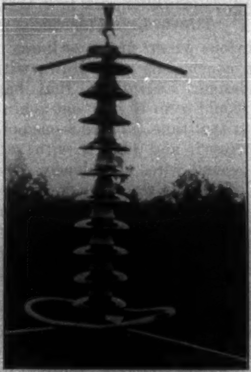

FIG. 7—RESULT OF TYPICAL FLASHOVER OF 132-KV. INSULATOR STRING WITH STANARD RING AND HORN PROTECTION

(Note burned ring above conductor; also horn tip slightly burned. Insulator undamaged)

2. In connection with the work discussed above and along the lines of limiting definitely the amount of overvoltage that can be brought into the station apparatus a reduction in the insulating value on the first mile or so of the line coming into the station was made, all with the idea of making certain that the lightning strength of the apparatus connected to the bus was

equal to, or greater than, the lightning flashover of the insulator string on the first mile of line.

3. In the design of the new lines, where the country did not absolutely demand it, the use of tower extensions has been kept at a minimum so as to keep the effective height of the line at a predetermined level, that level being determined, of course, by the tower design itself. In cases where the topography of the country permitted, the tension to which the conductor was pulled up was considerably reduced, resulting in a greater sag and a closer adherence of the conductor to the contour of the earth, with, of course, a net reduction of the average height of span above earth.

4. More attention was paid to the mechanical aspect of the arcing protection arrangements with a view of minimizing the effects of conductor vibration on the protection assembly itself.

### SUMMATION OF EXPERIENCE AND IT'S APPLICATION TO TOWER LINE DESIGN

In the previous paper[2] on these lines, presented in 1926, certain conclusions were drawn with regard to tower line design. Everything that has happened during 1926 would seem to bear out again the conclusions drawn at that time. There is one point only that should be stressed, and that is with regard to the question of ground wire. Previously it was pointed out that unless a line was very low, generally steel tower structures, carrying power conductors of 44,000 volts and over, should be designed and installed with a ground wire. It is now believed that careful consideration should be given to the question of whether or not two ground wires would not in some cases be justifiable with of course particular attention to the location of the ground wires as regarded the main conductors. The experience with lines without ground wires, and particularly the experience obtained during 1926 on the Logan-Sprigg and Turner-Logan lines, would seem to prove definitely that it is very hazardous and extremely unwise to try to operate a line of the type under discussion, without a ground wire. The limit to the voltage which can be picked up on an insulator string being the flashover of the string plus its supporting structure to ground, the likelihood of picking up voltages close to that limit will naturally be much greater without a ground wire than with it. This has been borne out by some of the 1927 experiences with klydonographs, to which reference will be made later. It is also further discussed in the 1927 report of the Transmission Committee of the Institute.[6]

### FUTURE DATA

During the past year, much more systematic record was kept of all cases of insulator and conductor damage although even that was not what it should be. In the future, however, an attempt will be made to have these trouble cases, so far as possible, definitely tied up with the cases of lightning trip-outs on the lines. The problem of patrolling 1000 miles of line does not lend itself to making a patrol after each thunderstorm, and it is usually the case that damage on the line can be assigned to some particular storm only in case such damage is sufficiently severe to cause a line outage that does not permit the line being placed back at once. One is faced therefore with the situation that unless an unusually heavy amount is spent on patrolling, it is impossible to tie up definitely each trip-out or to determine the concomitant damage. In this case, as in other cases of the same type, there is undoubtedly a happy compromise, and an attempt will be made to work this out.

### KLYDONOGRAPH INVESTIGATION

During the year 1927, in conjunction with the Lightning Subcommittee of the Committee on Transmission and Distribution of the Institute, a comprehensive klydonograph investigation was carried out on a portion of the above 132-kv. system. It is planned to continue this investigation during 1928, and at the end of that time, to summarize it before the Institute.

Acknowledgment of thanks is hereby made to the operating organization of the Appalachian Electric Power Company; to that of the Indiana & Michigan Electric Company and of The Ohio Power Company for their cooperation in gathering together the field data, and to Mr. I. W. Gross for his assistance in correlating it.

## Discussion

**W. S. Kates:** The statement is made that, "The isoceraunic lines, *i. e.*, lines connecting points of equal thunderstorm intensity, for the territory in question ranged from 40 to 60 in April, 150 to 200 in June and July, and down to about 60 to 80 in September."

I should like to know whether these figures refer to monthly periods and if they have been weighted in plotting the curve of Fig. 2.

I note in Table II that reference is made to outages due to lightning. As Mr. Sporn recognizes in his paper, the obtaining of accurate operating data is very difficult, and I should be interested to know what assumptions he made and what classification was made which determined that outages were due to lightning.

Mr. Sporn's paper initiates a type of record which has been lacking in publication to date, yet which is much to be desired. I refer to Mr. Sporn's attempt to correlate storm data with transmission-line performance.

Lack of such correlated data was apparent during a recent investigation of insulator protective-device performance. Proponents of protective devices during such investigation repeatedly stated that certain laboratory test performances are confirmed by operating experience. Usually the operating experience referred to was the statement that operation on a certain line was better after the installation of such a device than previously. Usually such statement was supported by figures of outages per mile during a season. For some of the lines referred to, the towers and insulators were designed for 100- to 150-kv. operation, yet operated only at 44 to 66 kv. In many such cases the protective-device installation was synchronous with the installation of the ground wire and the latter might have had equal or greater effect than the protective device. As Mr. Sporn differentiates, the ground wire is in the nature of a preventive device, whereas the insulator protective device is remedial. In only a very few operating records investigated was storm occurrence recorded or correlated. Yet the number of such storms seems a fundamental factor in the comparison of transmission line performance, because it determines the occurrence of most surges causing discharge.

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[2] Loc. cit.

[6] Report of Committee on Power Transmission and Distribution, TRANS. A. I. E. E., Vol. XLVI, 1927, p. 783.

A very striking illustration of the extent to which storm occurrence affects line performance when such line performance is stated on interruptions per mile basis is presented by the remark of G. H. Doan, while discussing Mr. Hemstreet's paper presented to the Institute, June 21, 1927 (Trans. A. I. E. E., 1927, p. 843). Mr. Doan mentions the operation of a 120-kv. system during the year of 1925 without a ground wire and with 114 automatic switch operations resulting. During the winter the line was equipped with a ground wire and the following year, 1926, there were only 7 operations. As Mr. Doan states, the switch operations were reduced 94 per cent.

From these facts as stated, and using outages per mile per year as a basis of comparison, it might be concluded that the ground wire of itself reduced automatic operation 94 per cent. However, Mr. Doan also states further that the storms passing over the transmission line area decreased 47 per cent in number. This latter statement places an entirely different complexion on any quantitative deductions from this operating record.

It is interesting to note also that one large operating company whose interconnected capacity is several hundred thousand kv-a. has, after correlating storm data with outages, decided that the essential factor in the elimination of outages is not remedial but preventive.

Storm intensity seems beyond determination or even approximation at present. Furthermore, transmission lines are economically justified on the basis of operating costs which do not include allowances for use of the lines as laboratories. The mere statement of the number of storms each season, however, would greatly enhance the value of operating records as guides for both designing and operating engineers.

**A. O. Austin:** As indicated by Mr. Sporn, there are many factors which must be taken into account in comparing the number of flashovers on various systems. While the length of line is usually the best possible base, it is necessary to take into consideration other factors such as difference in clearance, number of insulators or towers per mile, length of insulator string, and the benefit of ground wires. In addition, storms vary widely from year to year or in different localities. As yet we have no direct measure of the storm factor, but in the course of time we shall undoubtedly have improved means of recording and gaging this.

One point to which I should like to call attention is the use of the ground wire under conditions which may change its effectiveness materially. One of the most serious problems for the designer of the insulator or transmission line is to prevent the flashover of an insulator under an oscillation or after the crest of the wave has lowered materially.

Dr. Norinder has shown that while lightning may be aperiodic, severe oscillations are usually set up on the system. Line performance together with a study of the characteristics of the insulator has long indicated the presence of oscillations on many transmission systems which were undoubtedly causing flashovers not at the highest voltages, but rather at values considerably below the flashover voltage of the insulator under impact.

While there is little question as to the reduction of the maximum voltage at the point of disturbance by the use of the ground wire, its effect upon the attenuation or tail of the wave should be given careful consideration; otherwise, flashovers may result where the insulator system has a relatively low flashover voltage for an oscillation or with a wave having a slow rate of decay. Lack of attention to this factor may make it possible for a ground wire to subject the station to higher effective potentials than where none is used and to cause insulators to flash at a distance from the point of maximum disturbance or after the voltage has dropped materially. It is understood that the above applies to disturbances originating out on the system. Where a ground wire is used in the vicinity of the station only, it will result in lower voltages on station equipment due to its absorbing capacity.

Following the release of a bound charge $Q$, the resulting potential $E$ on the power conductor will be $E = \frac{Q}{C}$ where $C$ is the effective capacitance of the conductor to ground or objects of lower potential. The ground wire keeps the maximum induced voltage down by increasing $C$, 30 to 40 per cent, but has little effect upon the charge $Q$. The charge $Q$ upon the power conductor is practically the same with or without the ground wire, particularly where the clearances are large as in the higher-voltage lines. Since the losses on the power conductor are very high at the peak voltage, but drop off very rapidly as the voltage is decreased, it naturally follows that the losses on the conductor will be reduced materially by a reduction of 30 to 40 per cent in the peak voltage. Since the charge on the conductor is practically the same, the natural period will also be reduced owing to the increased capacitance, all of which tends to reduce the absorption of the abnormal voltage.

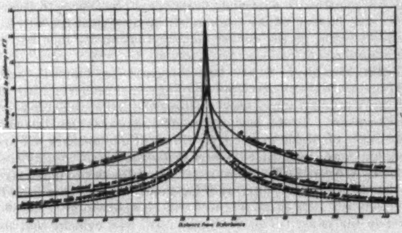

Fig. 1—Study Showing Effect of Ground Wire in Lowering Induced Voltage at Point of Disturbance and Increase in Voltage at the Station or Intermediate Points Over that Where No Ground Wire is Used

Lower Loss in Ground Wire Will Decrease Voltage at Point of Disturbance but Tends to Reduce the Absorption and Attenuation

This reduction in losses due to the lowering of the maximum voltage may result in a higher voltage at a distance in some cases as in $B$ in the accompanying illustration over that where no ground wire is used as in $C$. Where the flashover characteristics of the insulator are such that they will withstand the maximum voltage under the steep wave front in $B$ and will not flash over on the tail of the wave or on a resulting oscillation, no flashover will take place on the line, although the station may be subjected to a more severe disturbance than where no ground wire is used. This is particularly true where the ground wire has a low resistance and an absorbing power insufficient to offset the decreased attenuation.

If, instead of a low-resistance ground wire, several high-resistance ground wires are used, the induced voltage and attenuation may be as shown in $A$. As the number and proximity of the ground wires, rather than their size, determines the increase in the absorbing capacity $C$, a greater number of high-resistance conductors may be used to reduce the peak voltage at the point of disturbance as in $A$. The total current induced in the high-resistance ground wires in $A$ will be greater than in $B$, and, if their resistance is high enough, the $I^2 R$ losses will be greater in $A$ than in $B$.

Since the energy producing a loss in the ground wire must come from the power conductor, it naturally follows that any loss in the ground wire must result in an absorption of energy in the power conductor which tends to cause an increased attenuation in the voltage on the conductor. This increased attenuation tends to reduce the voltage at a distance and also tends to dampen out an oscillation. Under this condition, the voltage at all points on the system will be lower where the ground wire is used than where none is present. Where a high-resistance ground wire is used, there may be an appreciable rise in voltage between the ground wire and ground at the center of the span. Even though this induced voltage may reach 100 to 200 kv. for severe disturbances, it will probably not reduce the efficiency of the ground wire more than 10 per cent which, I believe, is negligible compared to the absorbing value and increased attenuation due to the resistance.

As the cost of the ground wire is a very appreciable item on any system, its efficiency and effectiveness should be given careful consideration, for if improperly applied, a considerable expense may be incurred without any improvement in the operation of the system, whereas a ground wire of lower cost, but with better absorbing factors, might result in an improvement for all conditions existing on the system, not only out on the line, but in the station as well.

**John Murphy:** In the last paragraph on the fifth page Mr. Sporn makes a statement regarding some trouble on May 18 on the Windsor-Canton lines. He says both line wires broke on that occasion. In the next sentence he says that that line had practically no arcing protection. I should like to know if I am justified in assuming that the breaks occurred at an insulator.

**H. B. Vincent:** The author states that the record of damage to insulators, conductors, and hardware on the lines is not complete for 1926 so no attempt will be made to give specific data in the paper. This being the case, it is evident that an accurate analysis cannot be made with respect to attributing a particular outage or interruption to a specific damage. However, it would have been interesting and possibly very valuable at least to know what damage, that is, as a total, has occurred to the insulator, and particularly the damage to individual units with respect to their location in the string.

Assuming that the primary object of the overhead ground wire and insulator protective device is to reduce the number of flashovers, and secondly, to convert extended into momentary interruptions, the ideal protective device should also protect the porcelain from damage.

To illustrate my point, on a recent power test of insulator protective devices, a device installed at both top and bottom of a string of a given number of units functioned satisfactorily, in that no porcelain was damaged. The top portion of the device was then changed to a different type. On test, this new set-up disclosed that 2 units in the string had broken. Yet in both cases under operating conditions, in so far as interruptions to the system are concerned, the records would have been identical, as the damaged string undoubtedly would have held operating voltage.

So without a record of the physical damage, the true efficiency of any particular insulator protective device naturally can be questioned.

The author in Figs. 5 and 7 clearly shows the resulting damage due to lack of arcing protection, so one could infer that with the protection shown in Fig. 7 no damage would occur.

I should like to ask, therefore, if my inference is correct, namely, that in the performance record submitted, in those lines protected, as in Fig. 7, no insulators have been damaged.

**E. D. Eby:** Mr. Sporn's paper is another example of the increasing attention being given to the line insulation and its relation to connected apparatus. The amount of data collected and its analysis according to the various factors in the problem, must be and are of vital importance in forming conclusions which are expected to influence subsequent practise.

There is a two-fold purpose in these studies: one, the protection of the line, the other, protection of the station apparatus. While statistics on line construction and performance are being collected and made available for study, there are practically no correlated data presented pertaining to the transformers, oil circuit breakers, and protective equipment. Of course, the cases of transformer failure, bushing flashover, etc., are rare compared to insulator trouble; but if there could be presented along with the insulator data a statistical record of connected apparatus as regards general type or design, test voltages applied, flashover voltage in the case of bushings, kind of protective equipment used and how installed, and the nature of failures when such occur, it should become possible to analyze the latter much more intelligently, and to decide upon both line and apparatus design more accurately.

Might I suggest, therefore, that such tables as Mr. Sporn's paper contains be supplemented in this and similar instances with a record of the characteristics and performance of connected apparatus. This would be very useful, for example, in checking the selection of high-voltage bushings for transformers and oil circuit breakers. In the past this selection has been made without reference to the line insulation, being based almost wholly upon the system rating and the test voltage of the apparatus. Such data would serve to check former practise, and guide the designers of high-voltage apparatus at a time like this when the relation of line insulation and apparatus insulation is being closely scrutinized and in some respects undergoing marked revision.

**J. H. Cox:** (communicated after adjournment) In the solution of any lightning problem a large amount of data is necessary due to the scarcity of lightning strokes in any given spot. For this reason papers like Mr. Sporn's are very desirable; only by the summarizing of a large amount of operating experience can we obtain a check on the performance of various features of lines in connection with lightning.

In taking data on the performance of lines when subjected to lightning, it is quite important that data on the number of storms be included as was done by Mr. Sporn. The United States Weather Bureau has found that the number of thunderstorms in any locality per year is remarkably constant. It is therefore possible that many of the expressions to the effect that the lightning in 1925 was much more severe than in 1926 and 1927, are inspired by the improved performance of many lines during the past two years due to the installation of ground wires following 1925.

Mr. Sporn has mentioned the comparison of the lightning strength of line insulation and of apparatus. Such a comparison is significant when considering the effect on apparatus of impulses which have been relieved by flashing over the adjacent line insulation. It must be remembered, however, that from the point of view of continuity of service the impulse ratio of suspension insulators is unity. That is, when any impulse, with a duration equal to those of lightning surges, is only slightly higher than the 60-cycle crest flashover of the insulator, a flashover will result.

Mr. Sporn has made a practise of continuing the ground wires into the station structure. I have made some calculations on the effect on a traveling wave of discontinuing the ground wire at the last tower out of a station. At such a point there is a change of total surge impedance and there will be a partial reflection of the wave. Calculations indicate that this reflection will cause an increase of the surge of the order of 15 per cent. Therefore, it seems well worth while to bring the ground wires into the station structure, or even to increase the number of ground wires on the last few spans.

Mr. Austin stated in his discussion that a lightning stroke is followed by an oscillation. In klydonograph tests on all types and voltages of lines, at from 10 to 50 locations, mostly the larger number, over four years, not a single record has shown lightning to be followed by an oscillation except where a flashover has resulted, and only on isolated-neutral lines has the oscillation been of more than one or two highly damped cycles. It is recognized that the flashover of porcelain insulators is reduced when subjected to a sustained high-frequency oscillation, but since such oscillations never exist on lines except those with ungrounded neutral, and then only after a flashover has already occurred, one cannot be greatly alarmed at such reduction of flashover.

Mr. Austin states further that a flashover has been experienced when the voltage recorded was less than the 60 cycle crest flashover of the insulation, but he did not state the circumstances. In klydonograph tests, a flashover is frequently experienced and the corresponding voltage recorded very low. It has also been determined, however, that a very high-voltage surge attenuates to a small fraction of its magnitude in a very few miles, and there is absolutely no reason to believe in the above mentioned cases, that the flashover was caused by a low value of voltage. Undoubtedly a higher voltage existed at a distance from the measuring station, and the flashover took place at that point.

It is well known that the amount of protection afforded by ground wires is greater, the greater the geometric mean radius of the ground wires and the less the geometric mean distance of the ground wires from the conductors being protected. It is obvious, therefore, that two small ground wires are more effective than one large ground wire, and any means of increasing the geometric mean radius of the ground wire, without a proportionate increase of the geometric mean distance from the conductors being protected, is an improvement.

**Philip Sporn:** Mr. Kates has raised some questions with regard to the isoceraunic figures. The figures shown in Fig. 2 were obtained by dividing by 20 the isoceraunic figures as published in the *Monthly Weather Review* referred to. The figures published in the review give the total number of storms per month over a 20-year period. That is, all the storms in that month have been added together, and the figure 80, for example, means that over a 20-year period of Aprils, there were 80 storms. The average for one year, therefore, is of course 4.

The Weather Bureau, incidentally, has stopped gathering the data from which it obtained isoceraunic curves because their 20 years of observation have convinced them that any further data would be merely a further check on the data obtained so far; that over a period of years the data repeat so closely that there is no value in continuing the gathering of further data.

Mr. Kates also brought out the point that data as to storm occurrence are very important in the determination of the operating performance of lines, and they are particularly important in any attempt to draw conclusive information from the operating experience.

I wish to say that I decidedly agree with him, and on our system now we have inaugurated an arrangement for keeping very complete track of this, but I do believe that, in the absence of any other data, the information as given in the *Monthly Weather Review* referred to, can be utilized, and very effectively, in designing. That is, you don't have to keep data of your own, if you examine the information already obtained by the Weather Bureau, to see that it is fallacious to try and apply experience obtained, say, in California to line conditions in Florida or thereabouts.

In California, as I recollect it, the 20-year isoceraunic at the period of maximum storm runs from about 8 to 10. In Florida it runs around 360. Operating experience obtained, as I say, in California cannot be applied directly to design in Florida or design in territories such as those discussed in this paper, where we do not have quite the heavy storms that are experienced in the South, but where we are not far from it.

Another question that has been raised is how we obtain the outages due to lightning. We do not claim that the data are 100 per cent correct, but they have been obtained and checked very, very carefully. Three sources were utilized for obtaining them. In the first place, arrangements had been made for a special record to be kept of those outages that did occur during lightning storms. The log of every station on the system was carefully scrutinized and every reference to a lightning storm checked with relay action. Then the relay records, which are kept independent of any other records, were again gone over, and whenever any one of the three sources showed possibility of lightning action, it was checked against the other two, and if it could be substantiated as a lightning record, it was accepted as such. If the majority of the data based on the three sources indicated that some other cause was responsible for the trip-out that cause was accepted and the lightning rejected as the cause.

In Mr. Austin's discussion, mention was made of a flashover at 400,000 volts on a system that I think could stand a crest voltage of 1,100,000 volts. We have had a very large number of klydonographs this year on our 132-kv. system and the system flashover value of that order, *i. e.*, 1100 kv., yet we have never obtained a record of a flashover at an insulator string where the klydonograph record showed as low a voltage. I think it would be very interesting if these data could be further substantiated.

Another point made by Mr. Austin in connection with the ground wire was that beneficial effects could be obtained on a low-voltage system by skipping the grounding on the poles. We have done that to a considerable extent, but have apparently secured something in addition to what we expected to get. That is, we never did it with the idea in mind of getting better action, but did it to save cost of grounding, and figured that the effectiveness of the ground wire was still sufficiently good even with the skipped grounding points.

A question has been raised as to just where the conductor broke, in the case of the conductor failure cited on the fifth page. Two wires were broken on one circuit and one on the other circuit. The middle wire was cut by lightning on No. 1 circuit at the point of attachment and it was apparently a clear flashover, or lightning break. The dropping of the middle conductor on the bottom phase of No. 1 circuit caused it to burn down and it, too, was broken as well as the bottom phase of circuit No. 2.

The top insulators of the strings on both middle and bottom phases on circuit No. 1 were burned, as well as the top insulators on the string on the bottom phase of the second circuit. The lines at this point were equipped with arcing horns on the line side only, but no damage was found on these horns.

Mr. Vincent in his discussion brought out the fact that he believed the function of the protective device was to hold back the number of flashovers, and later on, when the condition of flashover did occur, to prevent damage to the insulators. At 132,000 volts, I do not believe we get enough effect on the protective devices that have been developed so far, at any rate, to act much in the way of holding back flashovers. That is, we don't get sufficient grading at 132,000 volts to increase the lightning flashover of the string at high voltages, but at 220 kv. it indoubtedly does come into play. I do not think it comes into play at 132,000 volts.

Regarding the performance of the insulator strings with and without protective devices, particularly in Fig. 7, we have qualitative data—it is not quantitative, otherwise we would have published it—to show definitely that in general the trend is as shown by Figs. 5, 6, and 7; that is, we get very little burning, and in many cases none at all, with the protective devices, and we get considerable burning and in many cases heavy breakage where we don't use them.

In conclusion, we plan to continue these studies and hope that in the next few years we shall get much more valuable data.

# Vacuum Tube Synchronizing Equipment

BY T. A. E. BELT[1] and N. HOARD[1]
Member, A. I. E. E. Non-member

***Synopsis.***—*Potential from high-voltage circuits is obtained by means of capacitance transformers. This potential is applied to the grid circuit of vacuum-tube amplifiers, the output from which drives a rotating type of synchroscope. Thus the vacuum-tube synchronizing equipment makes unnecessary costly high-voltage transformers, which have been almost universally used for synchronizing in the past.*

*The paper describes the commercial apparatus, gives equations pertaining to the vacuum-tube amplifier and shows calculated and measured characteristic curves.*

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THE increasing number of power system interconnections makes synchronizing of high-voltage lines almost a necessity. Potential transformers for 110 kv. and above, which have been almost universally used for synchronizing, are costly. A new method of obtaining transformation from a high voltage to a low voltage by means of a simple capacitance, the amplification of this controlling potential to an appreciable amount of power, the utilization of the output from the amplifier for operating a rotating type of synchroscope makes possible, economically and practically, the almost universal adaptation of high-voltage synchronizing.

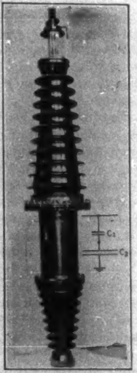

FIG. 1—132,000-VOLT BUSHING EQUIPPED WITH CAPACITANCE TRANSFORMER SHOWING FLEXIBLE LEAD AND SCHEMATIC DIAGRAM OF CONNECTIONS

*Description of Units.* The vacuum tube synchronizing apparatus as developed for commercial service consists of the following units:

a. Capacitance transformer bushing.
b. Outdoor amplifier.
c. Indoor amplifier and power supply.

*Capacitance Transformer Bushing.* Bushings equipped with capacitance transformers, (Fig. 1), are of the regular flanged-clamped oil-filled porcelain design, similar in external appearance and construction to the standard line of General Electric Company's oil-filled bushings. This added feature does not in any way affect the normal functions of the bushing when it is used with power apparatus. Where power apparatus bushings are not available and it is desired to use such a bushing, it may be mounted in a separate tank and installed in any convenient place, either in or out of doors (Fig. 2). The capacitance transformer enables these bushings to be used with vacuum-tube equipment in place of instrument potential transformers for synchronizing.

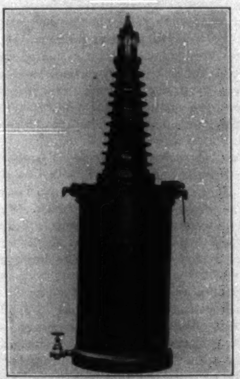

FIG. 2—CAPACITANCE TRANSFORMER BUSHING MOUNTED IN TANK

The necessary voltage for the grid-filament circuit of the amplifying tube is obtained from a high-capacity condenser within the bushing. This capacity is in series with the bushing capacity, the total line-to-ground potential of the system being impressed across both. The voltage obtained across either condenser is inversely proportional to the capacity. The secondary potential is approximately 35 volts. The high-capacity condenser consists of two layers of thin copper sheets separated by a treated paper dielectric and all

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[1] Both of the General Electric Co., Schenectady, N. Y.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., February 13-17, 1928.*

wound on a herkolite cylinder. The outer layer of copper is grounded to the ground sleeve and a soldered connection to the inner copper layer is brought out through a terminal, fitted in the ground sleeve. As shown in cross-section drawing, Fig. 3, this terminal is encased by a metal housing to prevent exposure of any live metal.

The outstanding features of this method for obtaining low potential from high-voltage transmission lines are:

a. Since the condenser is mechanically constructed within the ground-sleeve boundaries, the presence of external metal such as power apparatus tank, etc., does not have any effect upon the capacity and therefore the ratio of transformation remains constant.

b. Changes in atmospheric conditions, such as rain, snow, or air impurities deposited on the bushing surface do not affect the ratio of transformation.

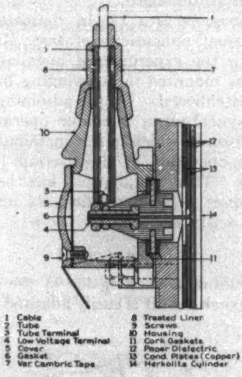

Fig. 3—Cross-Section Drawing Showing Method of Bringing out Terminal from Capacitance Transformer

c. Any normal temperature changes either increase or decrease both series capacities proportionally and, therefore, the ratio remains constant.

d. Since a very small load for the amplifying equipment is taken off the low-voltage side, the ratio is not affected.

e. The low secondary potential of approximately 35 volts in no way endangers the operation of the bushing or connected apparatus, even at potential which may flash over the bushing.

*Outdoor Amplifier.* The outdoor amplifier consists of a PT-210 power tube with its associated filament transformer and bias resistors mounted in a steel weatherproof box. This unit is a complete single-stage amplifier. The voltage obtained from the capacitance transformer is impressed on the grid of the tube and the output delivered to the primary of the interstage transformer which is located on the indoor amplifier panel.

The secondary potential from the capacitance transformer is divided by means of a 600,000-ohm potentiometer so that 17½ volts are delivered to the grid of the tube. The amplification constant of the PT-210 tube and the ratio of the interstage transformer are such that the voltage applied to the grid of the second stage of amplification on the indoor panel is 35 volts. The potential from the capacitance transformer cannot be successfully applied directly to the grid of the second-stage amplifier tube since the d-c. grid current of this tube with normal negative bias is sufficient when flowing through the 600,000-ohm resistance across the low-voltage terminals of the capacitance transformer to alter the effective bias

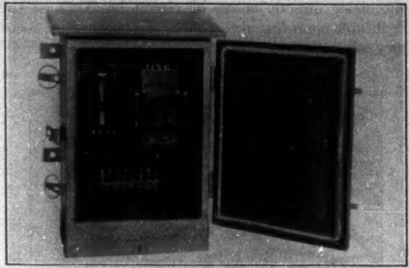

Fig. 4—Single-Unit Outdoor Amplifier

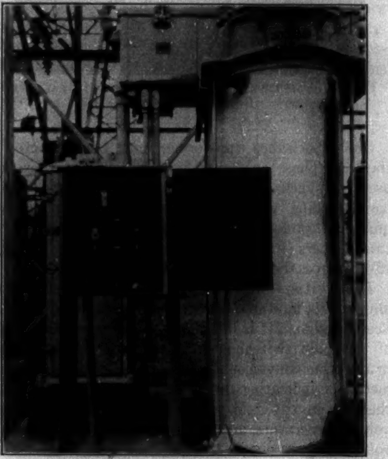

Fig. 5—Double-Unit Outdoor Amplifier

voltage, so that the tube operates on an undesirable portion of its characteristic curve. A single outdoor amplifier unit is shown in Fig. 4.

Two single outdoor amplifiers can be combined so as to make a double outdoor amplifier, as shown in Fig. 5. Double units are usually used when synchronizing directly across oil circuit breakers as this facilitates mounting and reduces the number of necessary connections.

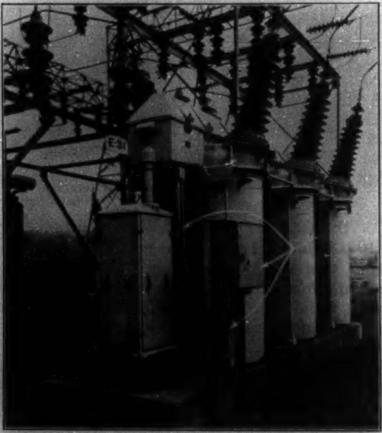

FIG. 6—VACUUM TUBE SYNCHROSCOPE INSTALLATION SHOWING OUTDOOR UNIT AND LEADS

One capacitance transformer must be connected to the same phase on each side of the oil circuit breaker used for synchronizing, and connections made to the corresponding grids of the amplifier tubes. These units are preferably mounted near the capacitance transformers (Fig. 6) in order to reduce stray capacity effects across the secondary side.

*Indoor Amplifier and Power Supply.* The indoor amplifier is mounted on a panel of standard switchboard design. It is intended for mounting along side of the main switchboard, although it can be placed in any other convenient location in the station. A voltmeter for indicating the plate voltage to the tubes, a rheostat in the field circuit of the plate and bias-voltage generators, and a fused switch for opening the voltage supply circuit to the motor generator set are located on the front of the panel.

On the back of the panel are mounted two separate single-stage power amplifiers requiring two PR-11A tubes. The undistorted power output which can be obtained from one of these tubes is approximately ten volt-amperes. The grid of each tube receives its excitation through the interstage transformer from the outdoor amplifiers. An output transformer is connected in the plate circuit of each tube and supplies 110 volts for operating the synchroscope. The slight phase shift in voltage through the amplifier and transformer is corrected at 60 cycles by connecting the proper value of capacitance load across the secondary terminals of the output transformer. A metal grill is provided for covering the apparatus mounted on the back of the panel. The plate connections are made under the grill which eliminates any exposed high-voltage circuits.

All power for operating the vacuum-tube equipment is obtained from a small four-unit motor-generator set. The power supply for operating the set can be taken from the station battery or any other suitable voltage source. An automatic starter is located on the indoor panel which puts the motor generator set in operation, as soon as the control circuit is closed, by insertion of the synchronizing plug in the proper receptacle in the switchboard.

The synchroscope is a 7½ in. diameter instrument giving the usual indications of fast, slow, and synchronism. In the experimental installation the synchroscope was mounted on a swinging bracket at the end of the switchboard. On the adjoining bracket was mounted a synchronism indicator operated from potential transformers which in this installation were used to check the operation of the vacuum-tube-operated synchroscope. This installation has been in daily service for over a year proving its simplicity and reliability in actual service.

## APPLICATION

The construction and operation of the synchroscope equipment is such that it is easily adapted for any number of incoming lines. When synchronizing is to be accomplished between a number of incoming lines and double busses each incoming line must be equipped with a capacitance transformer but it is only necessary to use one capacitance transformer for each bus. Such an arrangement is shown in Fig. 7. The act of synchronizing, using the vacuum tube equipment, is exactly the same as when potential transformers are used. Thus, the operator inserts the synchronizing plug which

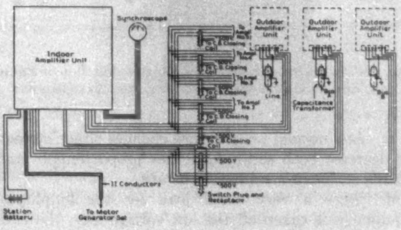

FIG. 7—SCHEMATIC LAYOUT FOR SYNCHRONIZING BETWEEN DOUBLE BUSES AND A NUMBER OF INCOMING LINES

automatically places the tube apparatus in operation causing the synchroscope to revolve in the usual manner.

It is of importance to note that one winding of the synchroscope may be excited from a potential transformer and the other winding excited from the vacuum tube amplifier without upsetting the phase relations on the synchroscope. A number of such installations have been made.

The life of vacuum tubes is relatively long and, from records of test data, should be about ten years of service operating on an average of fifteen minutes each day. Thus the maintenance of the apparatus is reduced to a very low degree.

## THEORY AND CHARACTERISTICS

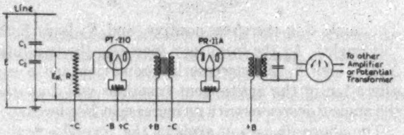

FIG. 8—SCHEMATIC DIAGRAM OF VACUUM TUBE SYNCHROSCOPE EQUIPMENT

The capacitance transformer has a constant ratio and zero phase-angle shift with varying frequency and voltage, provided there is no external circuit connected to it. When the potential of the capacitance transformer is applied to the amplifier, a resistance, *R*, Fig. 8, and the tube input impedance are connected in parallel with capacity, $C_2$. The tube impedance at 60 cycles, is very high as compared with the impedance of either $C_2$ or *R* and can be neglected. The relation between $\dot{E}_R$ and $\dot{E}$ is expressed by the following equation:

$$\dot{E}_R = \dot{E}\left[\frac{j\,\omega\,C_1\,R}{1 + j\,\omega\,R\,(C_1 + C_2)}\right] \qquad (1)$$

in which $\omega = 2\,\pi\,f$, and the other symbols refer to Fig. 12. Both the voltage ratio and the phase-angle shift of the capacitance transformer and resistance combination, can be obtained from this equation.

This equation shows that the voltage ratio $\dfrac{E}{E_R}$ is independent of voltage but varies with frequency and resistance. A numerical example will show the mangitude of these variations. A particular 110-kv. (63.5-kv. line-to-neutral) installation has the following constants; $C_1 = 0.000050\ \mu$ f, $C_2 = 0.0772\ \mu$ f, and $R = 600{,}000$ ohms. The variation of voltage ratio with resistance is shown by the curves *B* and *C*, Fig. 9. The calculated curve *B* checks the measured curve *C* very closely. These curves show that the voltage ratio does not appreciably change with a considerable decrease in resistance. Therefore, the ratio is independent of leakage change within the capacitance transformer, which measurements show to be approximately 100 megohms or more. The ratio of the capacitance transformer mentioned above is 1547 at 60 cycles. At 50 cycles the ratio is increased 0.05 per cent and at 70 cycles it is decreased 0.04 per cent, hence the ratio may be considered independent of frequency.

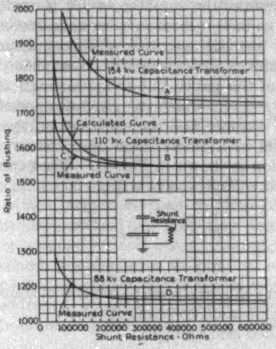

FIG. 9—RATIO CHARACTERISTICS OF CAPACITANCE TRANSFORMERS

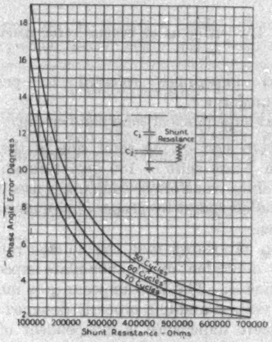

FIG. 10—PHASE-ANGLE CHARACTERISTICS OF CAPACITANCE TRANSFORMERS

There is a phase shift through the capacitance transformer when a resistance is connected across it, and this phase shift is dependent on both resistance and frequency but is independent of voltage. A curve computed from equation (1) showing the variation of this phase-angle change with resistance is given in Fig. 10. Thus 600,000 ohms gives a phase-angle shift of 2.75

deg., 500,000 ohms 3.3 deg., and 700,000 ohms 2.4 deg. at 60 cycles. At 70 cycles and 600,000 ohms the phase-angle shift is 2.4 deg. At 50 cycles the shift is 3.3 deg. That is, the secondary voltage $E_R$ leads the line-to-neutral voltage a small amount, due to resistance load, and changes slightly with change in frequency.

The vacuum tube amplifier, which is used to supply the power to the synchroscope, has characteristics which affect the over-all operation of the equipment. The complete theory of a vacuum tube amplifier is beyond the scope of this paper, but an approximate theory will be developed to show its general operation. The schematic diagram and the equivalent diagram of the a-c. circuits of a single stage of transformer-coupled amplification is shown in Fig. 11. The expression for $E_0$, the load voltage, can be written

$$\dot{E}_0 = -\mu \dot{E}_g \frac{\dot{Z}_0}{\dot{Z}_T} \qquad (2)$$

where

$\dot{E}_0$ = Load voltage referred to primary of transformer
$\mu$ = Amplification constant of tube
$\dot{E}_g$ = Applied grid voltage

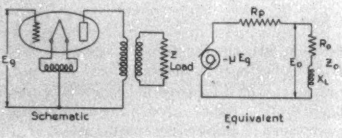

FIG. 11—DIAGRAMS OF SINGLE-STAGE AMPLIFIER

$\dot{Z}_0$ = Load impedance referred to primary of transformer
$\dot{Z}_T$ = Total impedance of tube-plate circuit.

The negative sign of the right side of the equation indicates a phase shift of 180 deg. through the tube itself, but since transformer coupling is used this phase shift can be corrected by proper choice of transformer connections.

Equation (**2**) shows that the voltage ratio of the amplifier is dependent on the tube-plate impedance and load impedance. The load impedance is independent of applied voltage and in a properly designed amplifier, the tube-plate impedance is independent of applied-grid-voltage. Under these conditions, the voltage ratio through the amplifier is constant for varying voltage input. Also, since these two impedances are independent of voltage, the phase shift through the amplifier is constant with varying voltage.

The effect of frequency changes on the operation of the amplifier can also be predicted from equation (**2**). This equation may be rewritten in the following form:

$$\dot{E}_0 = -\mu \dot{E}_g \left[\frac{R_0 + jX_L}{R_1 + jX_L}\right] \qquad (3)$$

where $R_1 = R_0 + R_p$ and, hence, is always larger than $R_0$. As $X_L$ increases with frequency, the fraction on the right side of equation (**3**) increases but approaches unity as a limit. This shows that the overall amplification of the stage increases with frequency, but approaches a definite limit. The percentage increase in voltage is less, however, than the percentage increase in frequency.

The phase angle between $E_0$ and $E_g$ can be obtained from equation (**3**) and is given by the following expression:

$$\theta = \tan^{-1}\frac{X_L}{R_0} - \tan^{-1}\frac{X_L}{R_1} \qquad (4)$$

Now $$R_1 > R_0$$

hence $$\frac{X_L}{R_0} > \frac{X_L}{R_1}$$

and $$\tan^{-1}\frac{X_L}{R_0} > \tan^{-1}\frac{X_L}{R_1}$$

The angle $\theta$ is therefore positive, and $E_0$ leads $E_g$ by this angle. As the frequency increases the two ratios $X_L/R_0$ and $X_L/R_1$ increase in proportion and a consideration of the antitangent functions will show that the angle $\theta$ decreases with an increase in frequency.

The above discussion explains the general operation of a vacuum tube amplifier with inductive reactance in the load. If, however, the secondary of the transformer is loaded with capacitance until the reactive component of the load impedance is capacitive then the term $jX_L$ in equations (**3**) and (**4**) is replaced by $-jX_c$. Under this condition it can be shown in the same manner as before that with an increase in frequency the amplification of the stage decreases, and the phase shift through the stage increases and is always negative.

The commercial apparatus utilizes a two-stage amplifier. Now, if $\theta_T$ represents the total phase-angle shift from phase voltage of line to voltage across synchroscope, $\theta_1$, the shift through the capacitance transformer, $\theta_2$ the shift through the first stage of amplification and $\theta_3$ the shift in the second stage then

$$\theta_T = \theta_1 + \theta_2 + \theta_3 \qquad (5)$$

By connecting sufficient capacitance in parallel with the synchroscope, the angle $\theta_3$ can be made negative and equal to $\theta_1$ plus $\theta_2$, and, hence, the total angle shift is zero. With a given capacity, this condition exists for one frequency only and the value of the capacity in the commercial equipment is so chosen as to compensate at the operating frequency.

The curve of Fig. 12 shows the angular error in position of the synchroscope when using the amplifier on one side and a potential transformer on the other. This is equivalent to the shift through the amplifier, as the angular error due to the potential transformer is negligible. The maximum error within the range of 50 to 70 cycles is only 7 deg., or only slightly greater than one min. on the dial of a clock. The device is, therefore, satisfactory when used in combination with a potential transformer.

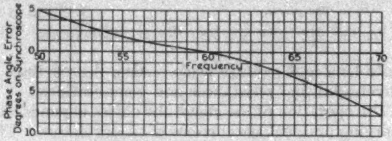

Fig. 12—Synchroscope Characteristic

One winding exciter from potential transformer
One winding exciter from vacuum tube amplifier

Fig. 13 is a curve showing the angular error when two amplifiers are used. In this case the maximum error is reduced to 3.3 deg. which is scarcely discernible on the synchroscope.

### SUMMARY

The capacitance transformer in no way affects the electrical characteristics or functioning of the high-voltage bushing in which it is mounted. The ratio is constant under changes in weather conditions. The secondary potential is 35 volts under normal operation, giving relatively low potentials under impulse flash-over of the bushing which in no way is dangerous to the apparatus used in conjunction with the bushing or to the circuits connected to the capacitance transformer. The cost of the capacitance transformer feature when added to a high-voltage oil-filled bushing is nominal.

The outdoor amplifier is mounted close to the capacitance transformer in order to reduce to a minimum the capacity effect introduced by connections. The power amplifier may be located any reasonable distance from the outdoor unit. Synchronizing with the vacuum-tube-operated synchroscope requires no unusual operation on the part of the operator.

The life of the amplifying tubes should be ten years or more, operating for a period of 15 minutes each day.

The ratio of the capacitance transformer is not affected by voltage change of the system; it changes with decrease in shunt resistance but is negligible with a decrease in resistance down to 300,000 ohms. The normal leakage resistance of the capacitance transformer is approximately 100 megohms, and therefore the ratio is independent of internal leakage. The ratio change is 0.05 per cent at 50 cycles and 0.04 per cent at 70 cycles, hence may be considered independent of frequency.

The phase-angle shift changes slightly with change in frequency, being 2.75 deg. at 60 cycles; 2.4 deg. at 70 cycles; and 3.3 deg. at 50 cycles with a 600,000-ohm shunt resistance.

The commercial apparatus utilizes a two-stage amplifier which introduces possible phase-angle errors which are compensated at operating frequency by connecting a capacity load across the output circuit. The maximum angular error in position of the synchroscope hand between 50 and 70 cycles, with one winding excited from a potential transformer and the other winding from the amplifier, is only 7 deg. or slightly more than one min. on the dial of a clock. It is therefore satisfactory when used in combination with a potential transformer.

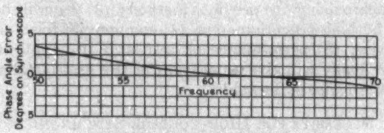

Fig. 13—Synchroscope Characteristic

Excited from vacuum tube amplifier

### ACKNOWLEDGMENT

The authors wish to acknowledge the help given by Mr. E. D. Eby and Mr. T. S. Farley who kindly assisted in obtaining the information for this paper.

## Discussion

For discussion of this paper see page 696.

# Condenser-Type Bushing

## Used With Synchronizing Equipment

BY E. E. SPRACKLEN,[1] Member, A. I. E. E.
D. E. MARSHALL,[2] Associate, A. I. E. E.
and P. O. LANGGUTH[2] Associate, A. I. E. E.

***Synopsis.**—This paper describes apparatus recently developed for utilizing the charging current of a condenser bushing in operating a synchronoscope, thus making a simple and inexpensive method of synchronizing at high voltage. Data are given also covering the operation of the device for different conditions of frequency, voltage, etc., thus assisting in the consideration of the adaptability of the device to other applications. An account of the first installation in the field is also given.*

THE rapid advancement of superpower systems has increased the demand for a simple and economical high-voltage synchronizing device.

In order to meet this demand there has been developed a condenser-bushing potential device which utilizes the inherent capacity potentiometer characteristics of the bushing in providing a source of low voltage which can be used in synchronizing.

This device is relatively inexpensive, is simple, easy to operate, requires small space, and is accurate enough for most synchronizing applications.

The following paper will discuss this device with particular reference to (1) reasons for high-voltage synchronizing, (2) previous methods, (3) general theory of bushing potentiometers, (4) commercial form of the device, (5) performance on test, and (6) application, and finally will give an account of the first installation of the device in the field.

### NECESSITY FOR HIGH-VOLTAGE SYNCHRONIZING

The locations where high-voltage synchronizing are advantageous are as follows:

1. At high voltage (110 kv. or over) switching stations where it is necessary to connect two systems and where no low-voltage circuits are available.
2. At high-voltage transformer stations where the high voltage is reduced to a medium value (approximately 66 kv.) and where the high-voltage synchronizer is less expensive than medium voltage potential transformers.
3. In stations where instrument potential circuits are available, but where extensive switching operations are necessary to use these instrument potential circuits for synchronizing.

### PREVIOUS METHODS AND THEIR LIMITATIONS

Hitherto there have been in general but two methods of reducing voltages for synchronizing. The first was the use of a potential transformer and the second was the use of a glow tube in connection with an insulator string. The disadvantages of the potential transformer are that it is expensive, bulky, and usually requires quite long high-voltage leads. Also, if used, fuses and current-limiting resistances add complications.

The operation of the glow-tube device depends on the charging and leakage currents of the insulators. Three glow tubes are connected to intermediate points on the insulator strings of the three phases. This connection produces an apparent rotation of the light intensity of the three tubes thus giving an indication of the relative frequency of the two systems.

This system has three inherent defects; the first is that the capacity of the insulators is small, and most of the current is leakage current on the surface of the insulator, subject to variations depending upon the cleanliness and amount of moisture upon the insulators. The second is that the glow of the tubes is faint, thus making the reading of the synchronoscope difficult. Third, the leakage and capacity of the lead wire to the synchronoscope reduce the current available for the tube. The combination of these effects may be such as to render the device inoperative at times.

### GENERAL THEORY OF BUSHING POTENTIOMETER

In general, a successful insulator potentiometer must have two qualities—it must be of a relatively high capacity and must be protected from the weather.

These two requirements are met by the condenser bushing. Constructed, as it is, of concentric metal-foil cylinders about the high-voltage conductor, it forms an ideal capacity potentiometer wherein the metal-foil cylinders are plates and the micarta is dielectric of a series of condensers which can be considered as connected in series from the high voltage to ground. By adding a tap to the last step to ground a potentiometer is easily obtained. Its size assures ample capacity for instrument indication and it is completely protected from the weather.

As these bushings are designed for a voltage drop of approximately 4000 volts per layer some means must be provided for lowering the voltage across the last step to the usual instrument voltage of about 110 volts. This may be done either by paralleling the last step with a condenser of sufficient size or by the use of a potential transformer.

The transformer method is the better as it allows a greater current to be drawn from the potentiometer than the condenser method does. However, with

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[1] Ohio Public Service Co., Cleveland, Ohio.

[2] Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., February 13-17, 1928.*

the transformer alone, as in Fig. 1, only devices which are specially calibrated can operate with accuracy. Any instrument having resistance in its circuit will cause the instrument voltage to be out of phase with the line voltage. This is shown in Appendix I. However, a modification of this method in which the terminal voltage and phase-angle error are practically independent of the burden of the connected instrument, may be applied.

This modification is effected by the addition of a reactor tuned to resonance with the capacity of the last step of the bushing less the transformer exciting reactance.

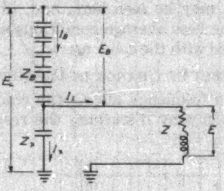


FIG. 1—THEORETICAL DIAGRAM OF SIMPLE POTENTIOMETER SCHEME

The theoretical circuit diagram for this connection is shown in Fig. 2. It differs from the circuit of Fig. 1 only in the addition of the reactor $Z_1$.

From the theoretical discussion of this circuit as given in Appendix II it is seen that the voltage ratio is approximately independent of instrument impedance and the phase angle between line and terminal voltage is approximately zero.

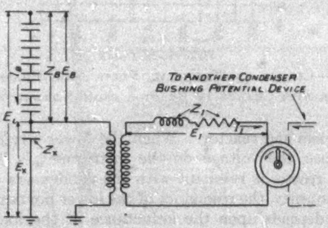


FIG. 2—THEORETICAL DIAGRAM OF POTENTIOMETER WITH RESONANT CIRCUIT

The final form of the device (Fig. 3) is somewhat different from the theoretical circuits so far shown.

A condenser is added to the secondary circuit of the device, and a spark-gap is connected across the primary of the transformer.

The condenser is added as a control of the no-load voltage of the device, and as a protection to the last step of the bushing.

The no-load voltage depends only on the potentiometer ratio of the condenser bushing and the ratio of the transformer. As the voltage across the instrument is approximately constant regardless of the burden, the voltage drop across the reactor and thus the voltage across the last step of the bushing must increase with load. Hence, the device operates with a variable voltage on the last step. It is desirable to keep this voltage just below or slightly above normal operating voltage as a safety measure for the bushing. This is done with the additional condenser as it causes the no-load voltage of the last step to be lower than normal, thus the transformer ratio is lower for a given instrument voltage and thus margin is given for a rise of voltage with instrument load. By this means the addition of the network does not interfere with the normal operation of the bushing.

As the load is increased the voltage across the last step rises. As a limit, at short circuit the lower network becomes a parallel resonant circuit and the only current then flowing in the upper part of the bushing is that necessary to supply losses in the transformer and reactor.

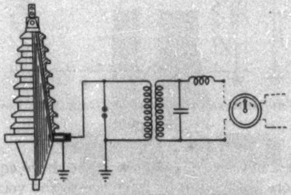


FIG. 3—COMPLETE SCHEMATIC DIAGRAM OF CONDENSER BUSHING POTENTIAL DEVICE

This causes the drop through the bushing to be small; hence the last step voltage must increase considerably. To protect the bushing a spark-gap is placed across the last step set to break down well below the dangerous voltage. This gap also protects the network against abnormal voltages due to lightning or other disturbances on the line.

When allowance is made for transformer iron loss, exciting current and impedance, the equivalent circuit diagram takes the form shown in Fig. 4.

All constants are referred to one side of the transformer. The exciting current is represented by the inductive component, the iron loss by the resistive component, and the last step capacity by the capacitive component of $Z_x$. The impedance of the transformer is represented by $Z_T$, placed back of the exciting impedance. The position of this impedance is somewhat in error but its effect on the performance is very small.

The value of the iron loss resistance varies with the frequency and the value of the exciting reactance varies with the saturation. The operating voltage of the transformer is known closely enough to allow these values to be determined by test.

The relation between $E_L$ and E is:

$$E_L = \frac{E}{Z}\left[\frac{1}{Z_c}\left(Z_B + Z_T + \frac{Z_T Z_B}{Z_x}\right)(Z_c + Z + Z_1) + \left(\frac{Z_B}{Z_x} + 1\right)(Z + Z_1)\right] \quad (18)$$

(The derivation of this expression is in Appendix III.)

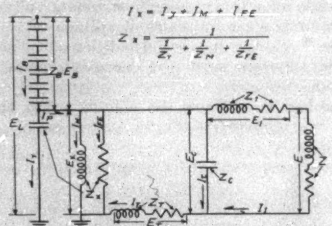


FIG. 4—THEORETICAL DIAGRAM OF COMPLETE POTENTIAL DEVICE

The effect of the various factors in the above equation can be more easily seen by reference to the vector diagram, Fig. 5, which was calculated from the above expression for a 132-kv. (76,200 volts to ground) bushing, carrying a 15-volt-ampere, 80 per cent power-factor load.

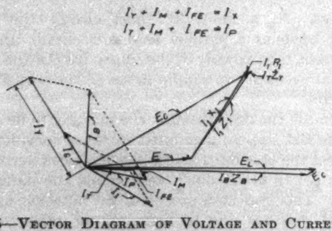


FIG. 5—VECTOR DIAGRAM OF VOLTAGE AND CURRENTS FOR CIRCUIT OF FIG. 6

It will be noticed that the iron loss of the transformer is in such a direction that it plays a considerable part in the amount of the phase angle between the line voltage and the instrument voltage. The effect of the impedance of the transformer, however, is very small.

### EFFECT OF CHANGE IN REACTANCE OF REACTOR

It is interesting to see the effect of changing the reactance of the reactor on the voltage and the phase angle of the connected instrument.

The curve, Fig. 6, was calculated from the above formula for the same 132-kv. bushing as the vector diagram Fig. 5. The burden was also 15 volt-ampere, 80 per cent power factor. The no-load voltage = 110. The value of the reactance was changed through the range shown. The load voltage and its phase-angle variation from line voltage was determined from the equation and plotted.

The curve shows that voltage regulation can be improved by decreasing the reactance but at the expense of angular accuracy. The vertical line shows the value of reactance for which resonance with the capacity is obtained. It may be seen here, and, in general, it is found that the best average conditions exist when the reactor is tuned with the condenser.

### EFFECT OF CHANGE IN FREQUENCY

A change in frequency affects the characteristics of the circuit chiefly by disturbing the resonance of the condensers and reactor. When the lower circuit is in resonance, the voltage on the instrument is highest. As the reactor is resonant with the condensers at normal frequency, the resonance of the lower portion of the device depends upon the inductance of the load. At unity power factor, the resonant frequency is the normal frequency and for inductive load the resonant frequency is lower. The resonant frequency of an electric circuit,

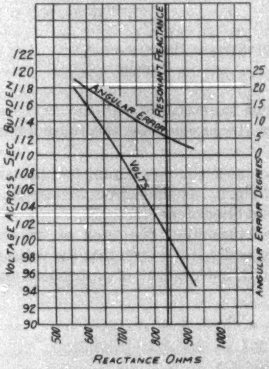


FIG. 6—CHANGE IN TERMINAL VOLTS AND PHASE-ANGLE ERROR WITH CHANGE IN REACTOR FROM NORMAL VALUE

$f_r = \frac{1}{2\pi}\sqrt{\frac{1}{L\,C}}$. From this it may be seen that the resonant frequency must drop with increase of inductance.

The curve in Fig. 7 shows the variation of voltage for a 110-kv. potentiometer, calculated for 15 volt-ampere at both 80 per cent and 100 per cent power factor. It will be noticed that resonance occurs at normal frequency for 100 per cent power factor, and at a lower value for 80 per cent power factor. As the frequency rises the voltage drops.

### INFLUENCE OF LINE-VOLTAGE WAVE SHAPE

If the line voltage is not of sine-wave form the effect of its harmonics on the voltage of the instrument connected to the potentiometer may be seen as follows:

In Fig. 7 the curve of voltage versus frequency shows that at 180 cycles (the third harmonic of 60 cycles) the voltage appearing at the terminals of the device is about 40 volts where the 60-cycle voltage is 108.

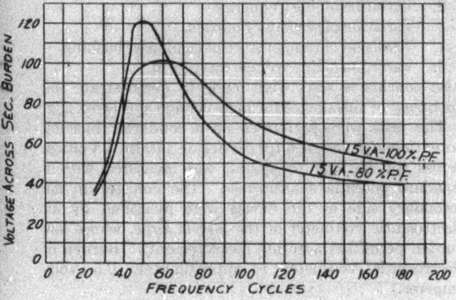
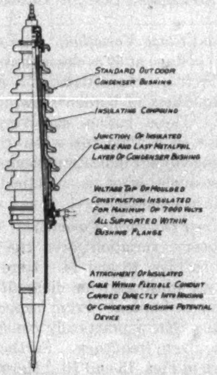


FIG. 7—THEORETICAL VARIATION OF FREQUENCY WITH VOLTAGE

The action of the circuit is such that it will not reproduce the harmonics of the line voltage at the instrument terminals. This causes an inherent error in r. m. s. voltage indication, dependent on the wave shape. The error, however, is slight for most cases.



STANDARD OUTDOOR CONDENSER BUSHING
INSULATING COMPOUND
JUNCTION OF INSULATED CABLE AND LAST METALFOIL LAYER OF CONDENSER BUSHING
VOLTAGE TAP OF MOULDED CONSTRUCTION INSULATED FOR MAXIMUM OF 7000 VOLTS ALL SUPPORTED WITHIN BUSHING FLANGE
ATTACHMENT OF INSULATED CABLE WITHIN FLEXIBLE CONDUIT CARRIED DIRECTLY INTO HOUSING OF CONDENSER BUSHING POTENTIAL DEVICE

FIG. 8—CROSS-SECTION THROUGH CONDENSER BUSHING SHOWING METHOD OF MAKING VOLTAGE TAP

For instance with a 10 per cent third harmonic the error is only 0.3 per cent.

### COMMERCIAL FORM OF DEVICE

As the name of the device implies, the condenser bushing is used to supply a source of potential. Fig. 8 illustrates in detail the method of tapping the last layer of the condenser bushing. A flexible cable having 7000-volt insulation is fastened to the last metal foil layer of the condenser and extended to a moulded fitting in the bushing flange. This fitting is of the "plug" and "jack" construction, having the tapped lead attached to the "jack." Fig. 9 illustrates the rigidity and simplicity of the tap construction. All material and clearances are designed to retain the insulating properties of the condenser bushings as at present, thus obviating any possible trouble between tap and ground. When the bushings are not connected to the potential device, a cap is provided for protecting the entrance to the "jack."

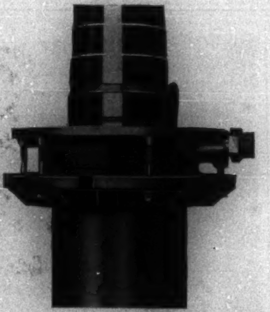


FIG. 9—VOLTAGE TAP CONSTRUCTION ON STANDARD CONDENSER BUSHING

The potential device, itself, excepting the synchronoscope, is assembled in a small protective sheet steel housing as illustrated in Fig. 10. It is suitably adapted for bolting directly to the circuit-breaker tank at a point near the condenser bushing tap. The connection between the tap and housing is approximately two to three feet in length, varying with the size of breaker. This connection consists of a 7000-volt insulated flexible cable protected within a flexible metallic water-proof conduit. Fittings are fastened to each end to permit ease of installation.

The equipment within the housing consists of a spark-gap arrester, low-voltage potential transformer, a reactor, and a condenser. The energy discharge across the gap is small and permits the use of the usual spark gap neutral arrester set to break down at a maximum voltage of 5500 volts. It is assembled within a porcelain casing and installed as shown in the upper left hand corner of the housing. Connection is made to ground through the protective housing of the device.

The low-ratio potential transformer as shown in the lower left hand corner of Fig. 10 is a standard indoor type. It is, however, equipped with a special winding to give the necessary variation required in adjusting the device to resonance. The transformer nominal ratio is 3800 to 200 and is designed to have very small losses, so that all possible energy is available for instrument use. One side of the transformer primary is grounded to the housing of the device.

The network reactor and condenser forming the external network is in the right hand side of the housing. The condenser has a maximum capacity of 4 $\mu$ f. and is rated and designed for 220-volt, 60-cycle service. The condenser and reactor are made variable for the purpose of adjusting the resonant condition of the network. The iron-core reactor is designed to have very high reactive factor, low energy loss, and constant impedance over the operating range of current. All wiring on the secondary side of the transformer is interconnected through the terminal block located in the lower right hand corner of the housing. This facilitates adjustment of the secondary circuit to obtain the proper performance of the device. Instrument leads are brought out through a conduit fitting in the bottom of the housing and can be handled the same as secondary leads of a potential transformer.

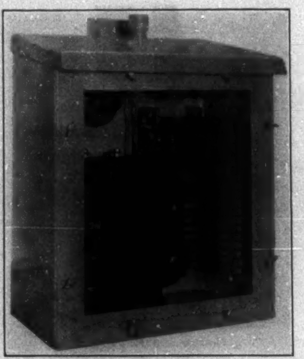


FIG. 10—HOUSING WITH COVER REMOVED SHOWING NETWORK

The outstanding point to be observed is the simplicity of the device. It is complete in one assembly and can be handled as a unit. The device is on the line at all times and operates continuously without any attention to auxiliaries or secondary potential sources. The actual synchronizing operation is accomplished as easily as with a potential transformer.

## PERFORMANCE

Variations in service and burden conditions will cause variations in the performance of the condenser bushing potential device. Extensive tests were made to determine the performance under different conditions and to obtain an idea of the limitations of the device. The scope of this investigation included performance under such conditions as:

1. Variation of line voltage.
2. Variation of line frequency.
3. Variation of secondary burden.
4. Variation of temperature of condenser bushing.
5. Variation of line voltage wave form.

Also conclusive tests were made to demonstrate the adequacy of this device for high-voltage synchronizing.

The tests were performed on a condenser bushing potentiometer designed for service on 110 kv. Voltage across the bushing to ground was measured with a standard potential transformer. The voltages on the secondary side of the device were measured by an electrostatic voltmeter of the Kelvin type, whose low burden permitted accurate measurement. (Burden of electrostatic voltmeter is approximately 0.5 volt-amperes.)

The device under test was adjusted to give minimum phase-angle error between the voltage across the bushing and the secondary voltage of the device when carrying rated burden.[3] (12 volt-amperes at 80 per cent power factor, based on 110 volts at 60 cycles.) This was obtained by using the transformer tap to give the desired no-load voltage and adjusting the condenser and reactor to give proper full-load voltage and phase-angle error.

*Effect of Line-Voltage Variation.* The effect of the variation of line voltage at 60 cycles is shown in Figs. 11 and 12. The voltage characteristic is practically a straight line regardless of burden showing practically constant ratio. These curves can very easily be adapted for use as calibrations when the device is used for obtaining voltage indications from high-voltage systems. Phase-angle error is practically constant with variation in line voltage.

*Effect of Line-Frequency Variation.* The general effect of frequency variation over the commercial range is shown in Figs. 13 and 14. Here the voltage characteristics are illustrated for different frequencies for a 15-volt-ampere burden. From inspection of both figures it appears that a practically constant ratio is obtained for a given frequency. Further frequency effects are shown in Figs. 15 and 16. Here it is evident that the resonant condition of the device is somewhat affected by frequency variation. Similar sets of curves may be drawn at other than 100 per cent voltage point. It is found that the frequency characteristic becomes flatter and thus more constant at lower values of line voltage. Another interesting performance is the effect of the power factor of the burden on the resonant condition of the network. The more resistive secondary burden flattens out the voltage frequency performance.

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[3] Note: All burdens given in the paper are in volt-amperes based on 110 volts at 60 cycles.

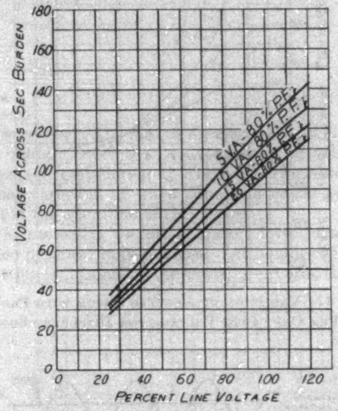

FIG. 11—VARIATION OF BURDEN VOLTAGE WITH LINE VOLTAGE AT 60 CYCLES. POWER FACTOR OF SECONDARY BURDEN—80 PER CENT (TEST DATA)

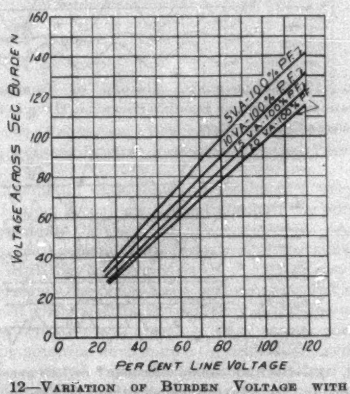

FIG. 12—VARIATION OF BURDEN VOLTAGE WITH LINE VOLTAGE OF 60 CYCLES. POWER FACTOR OF SECONDARY BURDEN—100 PER CENT (TEST DATA)

The phase-angle variation between the voltage applied to the bushing and the voltage of the secondary burden is illustrated in Fig. 17. Here is shown the effect of both burden and frequency. This same set of curves holds practically the same regardless of voltage variation; that is, at 60 cycles the phase-angle error will be 6 deg. regardless of the line voltage.

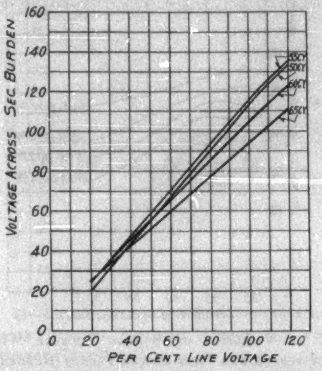

FIG. 13—VARIATION OF BURDEN VOLTAGE WITH LINE VOLTAGE AT 15 VOLT-AMPERES—80 PER CENT POWER FACTOR BURDEN, FOR VARIOUS FREQUENCIES (TEST DATA)

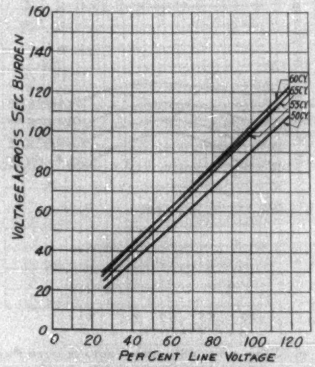

FIG. 14—VARIATION OF BURDEN VOLTAGE WITH LINE VOLTAGE AT 15 VOLT-AMPERES—100 PER CENT POWER FACTOR BURDEN, FOR VARIOUS FREQUENCIES (TEST DATA)

*Effect of Secondary Burden Variation.* The characteristics illustrating the effect of burden are included in all of the performances mentioned above. The voltage regulation over the range of burden given is very satisfactory considering the rated burden of the device. Although the burden is changed, the voltage characteristic remains a straight line for a given frequency. The power factor of the burden appears to have little effect on voltage performance as shown in Figs. 11 and 12. However, power-factor change affects the frequency-voltage characteristic and causes the resonant point of the device to be slightly shifted resulting in curves as shown in Figs. 15 and 16.

*Effect of Temperature Variation.* Data were obtained regarding this condition by heating a condenser bushing up to 140 deg. fahr. While cooling, the values of secondary voltage and phase angle were obtained at different secondary burdens down to 60 deg. fahr. The phase-angle variation was negligible while the voltage variation amounted to two and one-half per cent for a burden of 15 volt-amperes at 50 and 60 cycles. It is evident that the heating of the condenser bushing in service will cause little effect on the operation of the device.

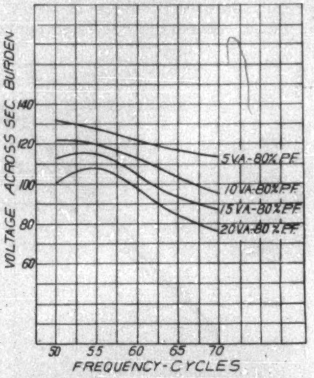

Fig. 15—Variation of Burden Voltage With Frequency for 80 Per Cent Power Factor Burdens. Line Voltage 100 Per Cent (Test Data)

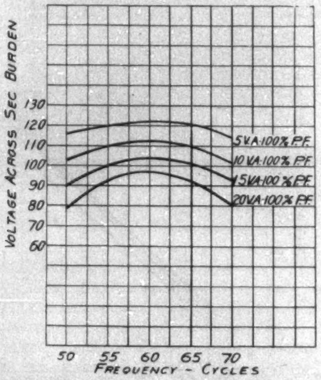

Fig. 16—Variation of Burden Voltage with Frequency for 100 Per Cent Power Factor Burdens. Line Voltage 100 Per Cent (Test Data)

*Effect of Wave Form.* All of the above curves and information are based on sine-wave form of line voltage. In Fig. 18 is shown an oscillogram illustrating the wave form of current and voltage within different parts of the device. The supply voltage, according to analysis, is practically a sine wave having only three per cent each of the third and fifth harmonics.

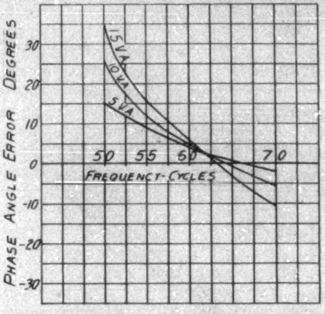

Fig. 17—Variation of Angular Error with Frequency at 100 Per Cent Line Voltage for Different Secondary Burdens

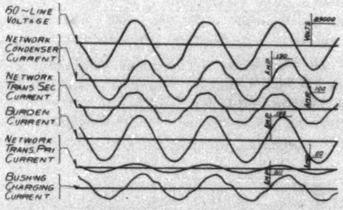

Fig. 18—Oscillographic Record of Currents and Voltage in Condenser Bushing Potential Device. Slightly Distorted Voltage Wave

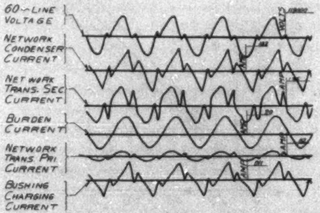

Fig. 19—Oscillographic Record of Currents and Voltage in Condenser Bushing Potential Device. Badly Distorted Voltage Wave

In Fig. 19 oscillographic performance is given. The same conditions of voltage, frequency, and burden exist as before except a poor wave form of voltage was arbitrarily caused by inserting a regulator in the supply and caused to operate at high saturation. Analysis of the supply voltage gave:

1st Harmonic—100 per cent of first.
3rd “ —22.2 “ “ “ “
5th “ —12.0 “ “ “ “
7th “ — 5.3 “ “ “ “
9th “ — 0 “ “ “ “
11th “ — 0 “ “ “ “

$E_{r.m.s.} = \sqrt{(100)^2 + (22.2)^2 + (12)^2 + (5.3)^2} = 103.2$ per cent.

This was checked by actual measurement of the secondary voltage under the two conditions of wave form. In general, considering the above performance, commercial variation of wave form will cause very little affect in the operation of the device.

It is interesting to note the wave form of secondary burden obtained in both cases. Although considerable distortion is obtained in the capacity circuits, the reactor smooths out all variations and results in a very good wave form of secondary current through the burden.

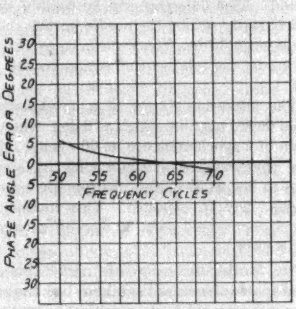

FIG. 20—PHASE-ANGLE ERROR WHEN SYNCHRONIZING WITH TWO CONDENSER BUSHING POTENTIAL DEVICES (TEST DATA)

*Performance Obtained with Synchronoscope.* A set-up was made to determine the operation of the synchronoscope with this device subjected to various conditions. Fig. 20 shows the phase-angle performance that may be obtained with variation in frequency of the line voltage. This information was obtained using similar condenser bushing potential devices on either side of the synchronoscope operated from the same line voltage source. The angular error is the deflection of the synchronoscope needle. This curve shows that the phase angle error is negligible when using two potential devices for synchronizing.

In Fig. 21 is shown the phase-angle performance when an attempt is made to synchronize with a condenser bushing potential device on one of the lines to be synchronized and a potential transformer on the other. The phase-angle error is permissible for synchronizing in the region of 60 cycles, but for greater ranges of frequency the device should not be used when balanced against a potential transformer. The variation of phase angle in either case is practically unaffected by variation in line voltage. The voltage performances obtained with a synchronoscope burden are illustrated in Fig. 22. Here, again, a constant voltage ratio is obtained for a given frequency. The performance with variable frequency is comparable to that discussed under effects of frequency. It appears, therefore, that the frequency variation will cause very little change in

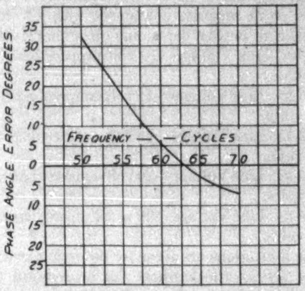

FIG. 21—PHASE-ANGLE ERROR WHEN SYNCHRONIZING WITH CONDENSER BUSHING POTENTIAL DEVICE AND POTENTIAL TRANSFORMER (TEST DATA)

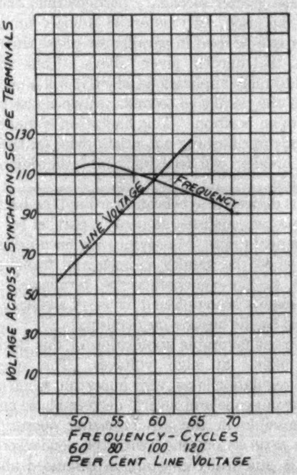

FIG. 22—VOLTAGE ACROSS SYNCHRONOSCOPE TERMINALS FOR VARIATIONS IN LINE VOLTAGE AND FREQUENCY (TEST DATA)

the voltage at the synchronoscope terminals. In general, these performance data indicate that synchronizing with the potential device on both sources to be synchronized will be just as reliable as is obtained in potential transformer practise.

### APPLICATION

This device may be applied to the standard condenser bushings assembled on circuit breakers, power transformers or in separate containers with the following limitations in burden depending on primary voltage:

1. 88-kv. Line Voltage—10 volt-ampere based on 110 volts.
2. 110-kv. Line Voltage—12 volt-ampere, based on 110 volts.
3. 132-kv. Line Voltage—15 volt-ampere, based on 110 volts.
4. 154-kv. Line Voltage—20 volt-ampere, based on 110 volts.
5. 220-kv. Line Voltage—30 volt-ampere, based on 110 volts.

These limitations are given for 60-cycle service. For 50-cycle service the burdens will be reduced to five-sixths of the above values. For 25-cycle service, the device should only be applied to the higher voltage bushings since the maximum burden permissible is but 40 per cent of the 60-cycle limits.

In case greater secondary burdens than those above are to be used, two potential devices on the same breaker can be used in parallel per phase thus allowing double the burden given above. This will apply mostly to relay applications where it will be permissible to open the paralleled secondaries when the breaker is in the open position. This limitation is made because the condenser bushing potential device on the line side of the breaker will feed back into the device on the other side.

If it is desired to synchronize around the breaker with the same two equipments used in parallel for relaying, arrangements must be provided for opening the secondaries when the breaker is open and transferring the voltage to the synchronoscope terminals. This all can be readily accomplished by use of auxiliary switches operated by the breaker mechanism.

The most favorable application of this device is for synchronizing at high voltages. The question of voltage regulation is not very important when operating a synchronoscope and several degrees phase angle error is permissible in the synchronizing operation. The voltage ratio as obtained with the condenser bushing device is practically constant as discussed above. In addition when synchronizing with the use of two identical potential devices, the phase-angle error cancels out.

The use of a potential transformer on one line to be synchronized and a condenser bushing potential device on the other is not recommended. Station layouts should be made to anticipate the use of a condenser bushing device on each of the lines to be synchronized. Under this condition the maximum phase-angle differential that may be expected between any two condenser bushing devices throughout the commercial frequency range (50 to 70 cycles) is six degrees. This error is due to possible manufacturing variations within the potential device itself and is designed to be practically zero at 60 cycles. This small variation in phase-angle error will not interfere with the usual synchronizing operation.

When it is proposed to synchronize between a potential transformer connected between phase on one system and a potential device connected on a breaker bushing of another system, the conditions are changed considerably. There are two points to be considered:

1. When the potential transformer is connected between lines, the secondary voltage will be 30 deg. out of phase with the secondary voltage of the condenser bushing potential device, assuming zero phase-angle error in the potential device as well as in the potential transformer. This is due to the fact that the transformer measures the line-to-line voltage, and the condenser bushing potential device measures the voltage to ground. This difference can be readily taken care of by arbitrarily setting the needle on the shaft of the synchronoscope 30 deg. from its usual zero, in a direction depending on the relative connection to the potential sources.

2. The phase-angle error of a condenser bushing potential device may be as high as 6 deg. when carrying a burden of a synchronoscope at 60 cycles. However, if it is contemplated synchronizing at system frequencies as low as 50 cycles, phase-angle error as high as 30 deg. may be expected. This means that the synchronoscope would point 30 deg. off zero at instant of synchronism.

It may be feasible to synchronize under this condition provided particular care is taken by the operator. An alternative would be to mark additional synchronizing points on the synchronoscope dial corresponding to the different frequencies. This requires that the operator keep the frequency in mind when synchronizing.

The usual method of synchronizing with phase voltage instead of wire to neutral voltage eliminates any possibility of incorrect synchronizing due to "floating neutral." Where phase-to-neutral voltage is used a floating neutral, as is experienced in poorly grounded systems, may give false indication on the synchronoscope. If such a system condition is anticipated, then synchronizing should be accomplished by means of line to line voltage rather than line to neutral voltage. This would require the use of two condenser bushing potential devices, one on each of the two phases, with interconnection of the secondary of the network so as to obtain the equivalent of a line-to-line voltage.

### OTHER APPLICATIONS

There are several other uses of the condenser bushing potential device in addition to synchronizing. The same limitations with regard to phase-angle and voltage performances, as above mentioned will apply here also. In general on applying this device, the maximum permissible burden should not be exceeded. Otherwise the condenser bushing itself will be affected by increasing unduly the voltage across the tapped layer. Additional applications may be listed under three general headings:

1. Voltage indication
2. Frequency indication
3. Relay operation.

The potential device gives a very satisfactory indication of voltage although not accurate enough for power measurements. Voltage indication may be obtained between phase and ground or between phases depending on the relative connection of the secondary of the devices on the different phases. Standard switchboard voltmeters can be used with this device for giving voltage indication and connected the same as when using potential transformers. Curves similar to those given under performance can be used as a calibration if necessary.

Frequency indication of a high-voltage line is also easily accomplished by use of the potential device. Inasmuch as there is no frequency change within the device, a true indication of frequency will be given. The standard switchboard frequency meter can be used within the burden limitations of the device and handled the same as when using the potential transformer.

Probably one of the most important future applications of the condenser bushing potential device will be in the relay field. Generally, the device may be used in place of potential transformers for operation of potential relays provided the phase-angle and voltage performance characteristics are satisfactory for proper functioning. In view of the fact that the device operates continuously, a potential source is always present. Due to simplicity and economy as compared to potential transformers, the use of relay schemes requiring potential should become more general. It will be particularly useful where protection is obtained by voltage indication between phase and ground, since the secondary voltage of the device is proportional to the voltage from phase-to-ground rather than between phases. This type of protection is in popular use on low-voltage circuits and its use has been hampered on high-voltage circuits due largely to the expense of potential transformers. Protection requiring the use of phase-to-phase voltage may also be obtained by proper interconnection of the secondary phase leads.

## FIRST INSTALLATION

The first installation of this high-voltage synchronizing device has been made at the Bluebell Substation (Alliance, Ohio) of the Ohio Public Service Company with very satisfactory results.

Bluebell Substation is located near the center of a 132-kv. transmission line 45 miles long, between Canton, Ohio and Warren, Ohio. Since no other load is tapped from the line between Canton and Warren, synchronizing at either terminal point is possible without affecting the Bluebell Substation supply. This, however, requires that synchronizing be accomplished using low voltage circuits and necessitates considerable switching operation. At the time the station was built it was considered too expensive to install 132-kv. potential transformers for synchronizing purposes only.

During the spring of 1926 an Electrostatic Glow Meter was installed, to provide a means of synchronizing more rapidly, and with fewer switching operations. While this installation was quite economical, it was reliable only under favorable weather conditions.

In order to obtain a device operative under all conditions, the condenser bushing potential device was installed in August, 1927. The cost was but slightly in excess of the electrostatic glow meter installation cost and upon investigation it was found to be less than one-sixth the cost of a potential transformer synchronizing installation. This new scheme, although more simplified, has all the advantages of the standard potential tranformer scheme but none of the irregularities of the glow meter scheme.

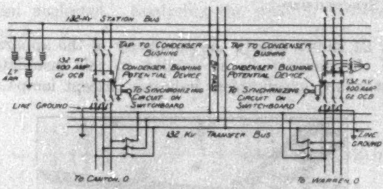

FIG. 23—STRUCTURE DIAGRAM—BLUEBELL SUBSTATION—OHIO PUBLIC SERVICE COMPANY, ALLIANCE, OHIO

In Fig. 23 is shown a schematic diagram of the 132-kv. busses in the Bluebell Substation, indicating particularly the relative connections of the condenser bushing potential devices. A detailed wiring diagram of the potential device connections is shown in Fig. 24. Here is illustrated the method of handling the secondary circuit. Similar procedure is followed as in potential transformer practise.

Fig. 25 shows one of the potential devices, with cover in place and with cover removed as installed on the 132-kv.—"G-2" oil circuit breakers. The units are mounted on pedestals at one tank of each circuit breaker. The field installation of the complete potential device consisted of the following:

1. Attachment of housing to pedestal and installation of pedestal. (For future installations, lugs will be provided on the circuit breaker tanks for bolting.)

2. Attachment of protected flexible cable to the tap on the condenser bushing and to the unit.

3. Attachment of the secondary leads from the

device to the synchronizing switch located on the station switchboard.

In Fig. 25 the tap from the condenser bushing may be seen entering the top of the potential device and the conduit carrying the low-voltage lead from the unit to the switchboard may be seen entering the ground at the base of the supporting pedestal. From the unit to the switchboard the insulation through the station control ducts is 600 volts. The wiring diagram in Fig. 24 shows clearly the simplicity of the apparatus and the connections as applied to this installation. A standard synchronism indicator, except lamps and standard synchronizing plugs or switches are used on the switchboard.

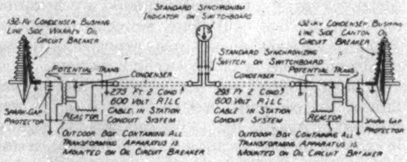
STANDARD SYNCHRONISM INDICATOR ON SWITCHBOARD
132-KV CONDENSER BUSHING LINE SIDE WARREN OIL CIRCUIT BREAKER
132-KV CONDENSER BUSHING LINE SIDE CANTON OIL CIRCUIT BREAKER
STANDARD SYNCHRONIZING SWITCH ON SWITCHBOARD
POTENTIAL TRANS
CONDENSER
CONDENSER
POTENTIAL TRANS
275 FT 2 COND 600 VOLT R.I.L.C CABLE IN STATION CONDUIT SYSTEM
295 FT 2 COND 600 VOLT R.I.L.C CABLE IN STATION CONDUIT SYSTEM
SPARK-GAP PROTECTOR
REACTOR
REACTOR
SPARK GAP PROTECTOR
OUTDOOR BOX CONTAINING ALL TRANSFORMING APPARATUS IS MOUNTED ON OIL CIRCUIT BREAKER
OUTDOOR BOX CONTAINING ALL TRANSFORMING APPARATUS IS MOUNTED ON OIL CIRCUIT BREAKER

FIG. 24—SCHEMATIC DIAGRAM OF OIL CIRCUIT BREAKER—CONDENSER BUSHING POTENTIAL DEVICE AND CONNECTIONS FOR SYNCHRONIZING

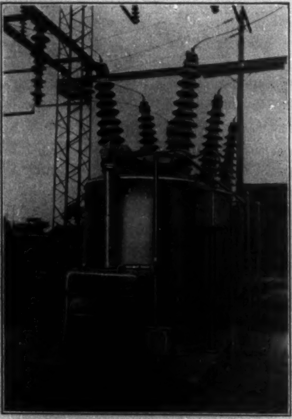

FIG. 25—CONDENSER BUSHING POTENTIAL DEVICE AS INSTALLED ON BREAKER TANK

It is the intention on future installations to synchronize across one pole of each breaker rather than from breaker to breaker in order to permit a greater flexibility in the switching set-ups and simplify switchboard connections. To date, 50 synchronizing operations have been made using the two condenser bushing potential devices with no incorrect indications.

## Appendix I

In the diagram, Fig. 1, the transformer is neglected and the constants are referred to one side of the transformer. The symbols used are defined by reference to the diagram.

$$I_s = \frac{I_1 Z}{Z_s} \tag{1}$$

$$I_B = I_s + I_1 = I_1\left(1 + \frac{Z}{Z_s}\right) \tag{2}$$

$$E_B = Z_B I_B = Z_B I_1\left(1 + \frac{Z}{Z_s}\right) \tag{3}$$

$$E = I_1 Z \tag{4}$$

$$E_L = E_B + E = I_1\left(Z_B + \frac{Z Z_B}{Z_s} + Z\right) \tag{5}$$

$$E_L = \frac{E}{Z}\left(Z_B + \frac{Z Z_B}{Z_s} + Z\right)$$

$$= E\left[Z_B\left(\frac{1}{Z} + \frac{1}{Z_s}\right) + 1\right] \tag{6}$$

Then the ratio of the potentiometer

$$= \frac{E_L}{E} = \left[Z_B\left(\frac{1}{Z} + \frac{1}{Z_s}\right) + 1\right] \tag{7}$$

It is interesting to substitute $Z = \infty$ in equation (7) as a check on its accuracy. Then

$$\frac{E_L}{E} = \left[Z_B\left(\frac{1}{\infty} + \frac{1}{Z_s}\right) + 1\right] \tag{8}$$

$$= \left[\frac{Z_B}{Z_s} + 1\right] = \frac{Z_B + Z_s}{Z_s}$$

This gives the ratio of the potentiometer at open circuit as proportional to the total impedance of the bushing divided by the impedance of the last step.

The effect of load may be seen as follows:
Substitute the following terms in equation No. (7).

$Z_B = -j X_B$ (capacity reactance only)
$Z_s = -j X_s$ (capacity reactance only)
$Z = R \pm j X$ (Resistive with either inductive or capacitive reactance)

Then the ratio

$$\frac{E_L}{E} = \left[-j X_B\left(\frac{1}{R \pm j X} + \frac{1}{-j X_s}\right) + 1\right]$$

$$= \left[\frac{-j X_B}{R \pm j X} + \frac{X_B}{X_s} + 1\right] \tag{9}$$

In order that the ratio $\frac{E_L}{E}$ be a numerical quantity, that is that there be no phase angle between $E_L$ and $E$, all $j$ quantities in the above equation must cancel. By inspection it may be seen that for any value of load resistance, $R$, except zero the $j$ terms will not cancel and there will be an angular difference in phase between the line voltage $E_L$ and the instrument voltage $E$. If an instrument having negligible resistance such as an electrostatic voltmeter, or some highly inductive circuit, were connected to the terminals of the above device the value $R_1 = 0$, and equation (**9**) becomes:

$$\frac{E_L}{E} = \left[\frac{-j\,X_B}{\pm j\,X} + \frac{X_B}{X_x} + 1\right]$$

$$= \left[X_B\left[\frac{1}{\pm X} + \frac{1}{+X_x}\right] + 1\right] \quad \textbf{(9a)}$$

here all the $j$ terms have canceled out, $\frac{E_L}{E}$ is a numerical value and hence the phase between $E_L$ and $E$ is zero.

It is interesting to note that if $\pm X = -X_x$, or if the load is highly inductive with negligible resistance and is resonant with the last step of the bushing $X_x$, the ratio $\frac{E_L}{E}$ would equal 1 and full voltage would be impressed across the transformer primary thus causing its ruin. This case is practically never attained completely in practise but it can be approached closely enough to be dangerous.

## Appendix II

A working knowledge of the action of the circuit in Fig. 2 can best be gained by dividing it into two parts, considering each separately and then uniting the action of the two to approximate the action of the whole circuit.

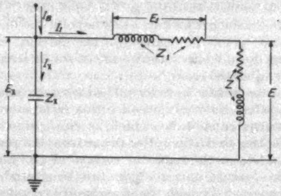

Fig. 26—Theoretical Diagram of Lower Portion of Potentiometer

Let the first part be the impedance of the bushing from the inner conductor to the tap $Z_B$ (Fig. 2). The second part will then be the rest of the circuit including the last step of the bushing $Z_x$, the transformer, the reactor $Z_1$, and the burden of the synchroscope.

Assuming a bushing of 21 steps, the impedance of the first part $Z_B$ will be 20 times the impedance of the last step $Z_x$. The impedance of the network is designed so that its total impedance, including the last step is never much higher than the original impedance of the last step $Z_x$. With change of load the network impedance will fluctuate but can be considered constant and equal to $Z_x$ with a relatively small error. Hence, under all load conditions, within the rating of the device, the charging current can be considered as equal to:

$$I_B = \frac{E_L}{(Z_B + Z_x)} \quad \textbf{(10)}$$

Substituting for $Z_B$ and $Z_x$ their values $-j\,X_B$ and $-j\,X_0$

$$I_B = \frac{E_L}{-j\,(X_B + X_0)} \text{ or } E_L = -j\,I_B\,(X_B + X_0)$$

approximately **(10a)**

The second portion of the circuit as shown in Fig. 26 is the same as the lower portion of Fig. 2 except that the constants of the circuit have been referred to one side of the transformer, and the transformer itself has been neglected. Analyzing the relation between $E$ and $I_B$:

$$I_B = I_1 + I_x; \quad \textbf{(11)}$$

$$I_x = I_1\,\frac{(Z_1 + Z)}{Z_x}; \quad \textbf{(12)}$$

$$I_B = I_1\left[1 + \left(\frac{Z_1 + Z}{Z_x}\right)\right] \text{ Substituting } \textbf{(12)} \text{ in } \textbf{(13)}$$

**(13)**

Substituting $I_1 = \frac{E}{Z}$:

$$I_B = \frac{E}{Z}\left[1 + \left(\frac{Z_1 + Z}{Z_x}\right)\right]$$

$$= E\left[\frac{1}{Z} + \frac{Z_1}{Z\,Z_x} + \frac{1}{Z_x}\right] \quad \textbf{(14)}$$

Now if $Z_1$ is pure inductance and equal to $j\,X_0$, and if

$$Z_x = -j\,X_0, \quad \textbf{(15)}$$

the relation between $I_B$ and $E$ becomes:

$$I_B = E\left[\frac{1}{Z} + \frac{j\,X_0}{-j\,X_0\,Z} + \frac{1}{-j\,X_0}\right]$$

$$= \frac{E}{-j\,X_0} \text{ or } E = -j\,X_0\,I_B \quad \textbf{(16)}$$

Thus it is seen that the relation between $E$ and $I_B$ is independent of the load impedance, $Z$. From (**10**) and (**16**) the ratio $E_L$ becomes:

$$\frac{E_L}{E} = \frac{-j\,I_B\,(X_B + X_0)}{-j\,I_B\,X_0} = \frac{X_B + X_0}{X_0} \quad \textbf{(17)}$$

Hence, the voltage ratio is approximately independent of instrument impedance and the phase angle between $E_T$ and $E$ is approximately zero. The greater the number of steps on the bushing the better will be the approximation.

A more exact solution for the circuit of Fig. 2 is not difficult, but any additional information it would give is of little value because the iron loss of the transformer plays an important part in the characteristics of the device.

## Appendix III

The derivation of Formula No. 18 is as follows:
From Fig. 4:

$$\text{Instrument Voltage} = E = I_1 Z \qquad (1)$$

$$\text{Reactor Voltage} = E_1 = I_1 Z_1 \qquad (2)$$

$$\text{Condenser Voltage} = E_c = E + E_1 = I_1 (Z + Z_1) \qquad (3)$$

$$\text{Condenser Current} = I_c = \frac{E_c}{Z_c} = I_1 \frac{(Z + Z_1)}{Z_c} \qquad (4)$$

Current Through Transformer Impedance $= I_T$

$$I_T = I_c + I_1 = I_1 + I_1 \frac{(Z + Z_1)}{Z_c} = I_1 \frac{(Z_c + Z + Z_1)}{Z_c} \qquad (5)$$

Transformer Drop $= E_T$

$$E_T = Z_T I_T = Z_T I_T \frac{(Z_c + Z + Z_1)}{Z_c} \qquad (6)$$

Volts on Lower Step of Bushing $= E_x$

$$E_x = E_T + E_c = \left[ Z_T I_1 \frac{(Z_c + Z + Z_1)}{Z_c} + I_1 (Z + Z_1) \right] \qquad (7)$$

$$E_x = I_1 \left[ \frac{Z_T}{Z_c} (Z_c + Z + Z_1) + (Z + Z_1) \right] \qquad (8)$$

Current into Combined Impedance $Z_x = I_x$

$$I_x = \frac{E_x}{Z_x} = \frac{I_1}{Z_x} \left[ \frac{Z_T}{Z_c} (Z_c + Z + Z_1) + (Z + Z_1) \right] \qquad (9)$$

Bushing Current $= I_B = I_x + I_T$

$$I_B = I_1 \left[ \frac{Z_T}{Z_c Z_x} (Z_c + Z + Z_1) + \left( \frac{Z + Z_1}{Z_x} \right) + \frac{Z_c + Z + Z_1}{Z_c} \right] \qquad (10)$$

Bushing Drop – Net Work to Line $= E_B$

$$E_B = I_1 Z_B \left[ \frac{Z_T}{Z_c Z_x} (Z_c + Z + Z_1) + \frac{(Z + Z_1)}{Z_x} + \frac{Z_c + Z + Z_1}{Z_c} \right] \qquad (11)$$

Line Volts to Neutral $= E_L = E_B + E_x$

Adding (11) + (8) and substituting (1) =

$$E_L = \frac{E}{Z} \left[ \frac{1}{Z_c} \left( Z_B + Z_T + \frac{Z_T Z_B}{Z_x} \right) (Z_c + Z + Z_1) + \left( \frac{Z_B}{Z_x} + 1 \right) (Z + Z_1) \right] \qquad (12)$$

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## Discussion

### VACUUM TUBE SYNCHRONIZING EQUIPMENT

(Belt and Hoard)

### USE OF CONDENSER TYPE BUSHING IN SYNCHRONIZING

(Spracklen, Marshall, and Langguth)

New York, N. Y., February 17, 1928

**E. D. Eby:** In connection with Fig. 8, it is mentioned that the value of the shunt resistance $R$ may vary appreciably from the normal value of 600,000 ohms without seriously affecting the ratio. If this shunt resistance should become very small, however, the ratio would be affected. It is interesting to note what effect upon the ratio would result from a low insulation resistance in the condenser $C_2$. This insulation resistance may be considered a part of the total shunt resistance since it is in parallel with $R$.

The insulation resistance of the condenser $C_2$ itself is normally of the order of 100 megohms, but this resistance may fall as low as one megohm without seriously affecting the ratio. With one megohm in parallel with a resistance $R$ of 600,000 ohms, the combined value would become 375,000 ohms, which from Fig. 9 is seen to affect the ratio to a negligible degree.

The phase-angle error is also dependent upon the value of $R$ as shown in Fig. 10. With the insulation resistance of condenser $C_2$ and connected leads as low as one megohm, and with $R$ equal to 600,000 ohms, the phase-angle error increases from 2.75 deg. to 4.4 deg. which is an unimportant change in the phase angle.

Thus it is seen that such a low value of insulation resistance of condenser $C_2$ and connected leads cannot seriously affect either the ratio of this capacitance transformer or its phase angle for synchronizing purposes.

The statement is made that the ratio of this capacitance transformer is independent of the presence of external metal structures. This has been demonstrated by testing capacitance-transformer bushings with large metal cylinders surrounding the porcelain shells so that the capacitance between bushing conductor and external objects is greatly increased. This was found to have no effect upon the transformer ratio. This is the result of complete shielding of the condenser $C_2$ by the ground sleeve of the bushing which extends beyond the ends of the condenser plates. That is, changes in the external capacitance of the bushing do not affect that part of its internal capacitance which determines the ratio.

Likewise, changes in the external leakage resistance of the bushing cannot affect the ratio because this resistance is in parallel with the external capacitance which, as shown above, may change without affecting the ratio. For this reason, the presence of rain, snow, dirt, etc., on the external surface of the bushing merely increases the leakage current from line to ground but does not change the current through the capacitance transformer.

Tests have also been made at varying temperatures which have shown no change in ratio. This is to be expected since the insulating materials in the condenser $C_2$ are of the same character as those used in the puncture structure of the bushing shown in Fig. 8 as $C_1$. Any changes in the permittivities of the insulating materials, therefore, affect both capacitances similarly.

As a further check on the ratio of the capacitance transformer under actual operating conditions, there is being set up on a 110,000-volt power system a parallel installation of capacitance transformer and standard potential transformer. Simultaneous readings of system voltage will be taken over a considerable period of time and under varying operating conditions. It is believed these observations will help to confirm the calculations and laboratory tests which indicate that the capacitance transformer may be used for metering as well as for synchronizing purposes.

A high degree of operating safety in this device is assured by the high safety factors employed in the design and construction of the capacitance transformer. At 60 cycles, the flashover voltage of the bushing is about 5½ times its operating voltage from line to ground. The puncture strength of condenser $C_2$ is about 100 times its operating voltage. This gives a safety factor of 100 at operating stress, and 18 above 60-cycle flashover. With impulse voltages, the safety factor is correspondingly high. This design of oil-filled bushing will withstand impulse flashover indefinitely, and the capacitance-transformer insulation is correspondingly strong. This is of the greatest importance to the operation of the synchroscope which may be called upon to synchronize lines during lightning storms.

Each capacitance-transformer bushing receives a 60-cycle flashover test as well as the usual one-minute high-potential test. The capacitance transformer receives a test of 1000 volts for one minute. The capacitance of each transformer is measured and the low-tension voltage calculated from the measured capacitance. A variation of ± 5 volts is allowed. Each capacitance transformer is calibrated with its vacuum-tube equipment.

Capacitance-transformer bushings of this type have been built for voltages from 88,000 to 220,000 volts. They can be supplied for lower voltages if desired. The additional cost of capacitance transformers in oil-circuit-breaker bushings is so small that they have been specified on some orders in anticipation of a possible installation of the synchronizing equipment at a later date.

**H. L. Crumley:** I have had some very good operating experience with the vacuum-tube synchroscope.

We have installed on the Metropolitan Edison system one outfit at the present time. We had no misgivings as to the reliability of the equipment. The only thing we were afraid of was what would happen with impulse voltages.

We had one experience that convinced us of the reliability of the outfit. One evening during a severe lightning storm, the line to which this synchroscope was connected was knocked out and in a few minutes it was resynchronized at the station using the vacuum-tube synchroscope. An inspection showed that the bushing of the capacitance transformer had been cracked, due to a flashover. This flashover was evidently the cause of the line trip-out.

Since we have seen what may occur from impulse voltages and even to the flashover of the bushing itself, we have no fear as to the future operations of this type of equipment.

**Philip Sporn:** (by letter) It has always been realized that in a high-voltage station consisting of a half dozen lines or so, and perhaps a series of transformer banks utilized for obtaining a distribution voltage, it would be highly desirable to be able to synchronize every line. However, cost considerations of potential transformers primarily, although there were others, very often dictated the elimination of direct synchronizing facilities especially if it was possible to figure out a sequence of switching under which synchronizing could be done at lower potentials at some other point. Now this arrangement, while it often looked very beautiful on paper, did not work quite as smoothly when put into the hands of a group of substation operators. The result has been that many high-tension stations that were originally designed without such synchronizing facilities, later had them put in at a very much greater expense because operating experience showed their almost absolute necessity.

These two papers point out means of doing this at very much less expense than was thought possible a few years ago. Of the two, the straight condenser method is apparently simpler but it appears to me that vacuum-tube method has more than enough other advantages to compensate. For one thing, at no point outside the breaker does any high potential exist. Again, it is highly desirable to get operating men familiar with, and used to operating and relying upon vacuum-tube devices. Today, it is possible to synchronize, to communicate, and to supervise operation with vacuum tubes; but ultimately we will surely use them for voltage regulators. Other uses are bound to follow. The power engineer therefore must make up his mind that the vacuum tube is going to be a tool and a piece of apparatus without which, in the years to come, he will not be able to get along on his power system, and that the sooner he gets the operating people thoroughly versed with it the better off everybody will be.

Messrs. Spracklen, Marshall, and Langguth point out that it is not recommended to use a potential transformer on one side to be synchronized against a condenser bushing on the other. Where, however, it is desired to meter at the high voltage and a set of potential transformers is utilized for that purpose connected to the bus, it would be most logical in that case to synchronize against the potential transformers. In such a case the vacuum-tube arrangement would have a slight advantage. On the other hand it is conceivable that the cost of the straight condenser arrangement may be sufficiently lower to make it possible to install, under such a set of conditions, an additional condenser bushing connected on the bus and yet not increase the cost over the vacuum-tube arrangement.

Neither paper mentions any costs. I think these might be of interest. In a 132,000-volt switching station that was cut into service within the last six months we had occasion to synchronize six circuits against either one of two buses. The cost of doing it by vacuum-tube arrangement ran close to $8400. The estimated cost of accomplishing the same thing by standard 132,000-volt potential transformers was $34,000.

**J. H. Cox:** (communicated after adjournment) The authors of this paper have confined themselves to normal-frequency applications of the condenser-bushing potentiometer. However, in addition to being useful for those applications it forms an ideal potentiometer for making measurements of transient voltages on transmission lines. In this application it is merely necessary to connect the measuring device between the tap and ground. Since the potentiometer is a capacity coupling the ratio of the voltages is constant regardless of magnitude or wave shape, so long as the measuring devise is also a capacity. Both the klydonograph and the cathode-ray oscillograph come in this

Fig. 1

category as the energy consumed by either is entirely negligible. The normal voltage on the tap, being 4000 volts, is above that required as the normal voltage on either of the above instruments. This may be reduced to any desired value by connecting a suitable external capacity in parallel with the instrument. This, of course, causes a voltage equal to the amount of the reduction to be impressed across the remainder of the bushing, but this should be negligible.

The three principal objections to the capacity potentiometers as commonly used in klydonograph tests are cost, space, and the change in ratio with varying weather conditions. Often a major part of the expense of a klydonograph investigation has been in the potentiometers; when the breaker, or transformer, bushings are provided with a tap there is little added expense, and even when installed specially they can later be used as spare bushings. Due to the mutual effect between adjacent air potentiometers they must be separated by considerable distance; the bushing potentiometers do not affect each other and may be spaced as close as safety permits. Of course, when apparatus bushings are used little additional space is required. The supporting insulators of the air potentiometers were subject to dirt and moisture, with a consequent change of ratio when the leakage became large enough to be important; the capacities in the bushing potentiometer are enclosed.

When used as transient-voltage potentiometers these bushings are not limited to the higher-voltage classes as they are for normal-frequency applications. They have been applied on systems with voltages as low as 6600 volts. Even these bushings have a capacity of about 300 micro-microfarads per step, which is ample to supply the klydonograph, which has a capacity of about 10 micro-microfarads. Also, for voltages of 25,000 and less the cost of condenser-bushing potentiometers is not too high to prevent their being built for special tests. Fig. 1 herewith shows a potentiometer, with a special tank, for 66,000 volts.

**T. A. E. Belt:** (communicated after adjournment) Since nothing is of more importance in high-tension apparatus than the bushing, I wish to bring out several points.

Assuming that the condenser bushing has a 60-cycle flashover of 5½ times its normal line-to-ground potential, and that the impulse ratio of the bushing is 2, it can be shown that approximately 60,000 volts may be obtained on the tap at the time of an impulse sufficient to arc over the bushing. If the tap is left isolated, adequate insulation and clearance must be provided for 60,000 volts. On the other hand, if the tap is grounded, the dielectric of a 110,000-volt bushing will be overstressed by approximately 6 per cent, that is, the bushing insulation will be operating at a reduced factor of safety. This reduction in dielectric strength, however, may be compensated by increasing the size of the bushing.

When the tap is used to supply potential for relays, a momentary flashover of the protective gap will cause momentary loss of voltage, which seemingly may cause incorrect relay operation.

A circuit described in an article in the *Siemens-Zeitschrift*, Vol. 6, Oct. and Nov. 1926, makes use of the condenser bushing. It is reported here that temperature affects the bushing characteristic. One case of trouble mentioned was caused by one bushing operating continuously in the shade while the other bushing at times was exposed to the sun.

**T. S. Farley:** (communicated after adjournment) The capacitance transformer described in the paper by Belt and Hoard produces a secondary voltage $E_R$ which has practically the same wave shape as the line voltage but reduced in magnitude. Eq. (1) shows that as the frequency increases, the ratio

$E/E_R$ approaches $\dfrac{C_1 + C_2}{C_1}$ as a limit, which for the capacitance transformer mentioned equals 1545. The ratio for 60 cycles is 1547. Hence it is evident that the magnitude of the fundamental and all harmonics are reduced in the same proportion. Also from Eq. (1) it can be shown that as the frequency increases the phase shift decreases to zero as a limit. The phase shift for 60 cycles is only 3.3 deg. and is less for any of the harmonics. Therefore it is seen that the secondary voltage of the capacitance transformer is a true representation of the line voltage including all harmonics.

Because of these characteristics of the capacitance transformer, it is very well adapted for use in conjunction with properly designed vacuum-tube circuits to supply potentials from high-voltage lines for accurate measurement work.

**T. A. E. Belt:** In addition to using the amplifying equipment for synchronizing, potential for other purposes may be obtained simply by energizing the outdoor amplifier independently of the indoor unit, thus obtaining the potential from a separate output transformer connected in the plate circuit of the amplifier tube.

Mr. Eby pointed out that in the design of the capacitance transformer, a high factor of safety was used to avoid dielectric failure under lightning impulses. It is gratifying to know that these precautions which were thought necessary in the design have proved to be worth while in operation; for Mr. Crumley tells us that even though the porcelain of a bushing was split by lightning and part of the oil gone, the capacitance transformer continued to function.

**E. E. Spracklen:** Although our experience with the equipment installed at Bluebell Substation has not covered a long period of time, we feel that its operation is quite dependable and that the voltage of the secondary circuit offers no serious hazard if the installation is properly made.

The simplicity of the complete circuit and the use of standard switchboard apparatus highly recommends this hook-up in the considerations of installation, operation, and maintenance costs.

Since the installation was made last August nearly one hundred operations of the synchronizing device at Bluebell Substation have been performed with very satisfactory results, and entirely without any need for adjustments or replacements of apparatus.

As brought out in our paper, the installation at Bluebell Substation was made partially with the idea of obtaining field experience with this synchronizing scheme and of obtaining data on the possibilities of the various applications for condenser bushings which may be accomplished economically, simply, and dependably. Up to this time nothing has occurred to change opinions regarding these applications and it is hoped that substantial data may be assembled in the near future.

**P. O. Langguth:** In connection with the condenser-bushing potential device, it is well to note the advantages that may be obtained with regard to use of auxiliaries on high-voltage circuit breakers. It is now possible to obtain both a current indication and a voltage indication from circuit breakers or other power apparatus which are equipped with condenser bushings.

This latest development which uses the charging current from a condenser bushing for operating synchronoscopes or other meters depending on voltage indication is very interesting. The device is rather simple and much less expensive than the usual potential-transformer installation. The condenser-bushing device is complete in one unit as shown in Fig. 10 of the paper. This comprises the complete equipment for use with the tapped condenser bushing. No separate source of power or vacuum tubes is required for use with this device. It is well to note that the secondary leads from the outdoor housing are handled in the same manner as the secondary leads from a potential-transformer installation. This device is sturdy, and requires no maintenance. Potential is available across the secondaries continuously as it is not necessary to disconnect the device from the primary when not in use.

There are four broad uses of this device. Due to the fact that potential is available in the secondary circuit at all times (*i. e.*, as long as the bushing is connected to the line) whether in a circuit breaker or power transformer, this device is not limited to synchronizing.

1. For operation of a synchronoscope for synchronizing high-tension lines between 88 kv. and 220 kv.

2. For operation of frequency meters. Since there is no frequency change in the potential device the frequency indicated on the secondary will be the same as the frequency of the line.

3. For operation of voltmeters. An indication of line voltage can be obtained since the voltage characteristic is practically constant.

4. For operation of relays.

The application of this device for relay protection of systems is more or less in the development stage. However, the future looks very bright in regard to use of this device for protection of systems against phase-to-phase and phase-to-ground faults. In fact, several large power systems are at present installing these devices for such protection. Reference should be made here to the paper[1] on "Relay Protection" given by Messrs. Crichton and Graves at the Regional Meeting in November. Relaying, of course, is made possible due to the fact that the secondary voltage of the condenser-bushing potential device is available at all times without any attention to auxiliaries, such as vacuum tubes.

I should like to say a word about the application of this device to relaying and synchronizing. In general, it has been the practise when using potential transformers to synchronize between lines or between phases. However, when using the potential device with the condenser bushing, the voltage obtained at the secondary device is in phase with the line-to-ground voltage and, of course, in that case synchronizing is based on the phase relation between line and ground. If it is desired to synchronize with a potential transformer which is connected to the bus for metering, it is necessary to install two condenser-bushing potential devices. The two devices would be installed on the phase to be synchronized and the secondaries connected in series, thus resulting in a secondary voltage, in phase with the phase-to-phase system voltage. In relaying between line and ground or between phases, it should be noted that each condenser bushing on the circuit breaker can be equipped with a potential device. Then with proper secondary interconnections all six devices may be used for synchronizing, relaying, voltage indication, or frequency indication without overloading the device.

In the previous discussion some mention has been made of the voltage tapped from the bushing. For example, the normal tap voltage is about 4000 volts for a 132-kv. condenser-bushing device. The synchronoscope or other potential instruments are insulated from this high voltage by the voltage transformer in the device. It is well to keep in mind that the impedance of the upper part of the bushing is in the neighborhood of 11,000,000 ohms; thus if the primary were short-circuited the maximum current that would flow is about 12 milliamperes. If the secondary of the device were short-circuited the maximum current would be approximately 250 milliamperes, which is too low to cause any serious damage.

If overvoltage occurs on the last step of the bushing the gap discharges with the above mentioned 11,000,000 ohms in series. The gap is set for 5000 volts and its discharge is limited to the above primary current, and thus when the voltage returns to normal the gap automatically ceases to discharge. The high capacity of the condenser bushing protects it from impulse voltages.

The high-voltage circuit of the device (4000 volts approximately) is completely enclosed in a grounded metallic housing and insulated within for 7000 volts. The danger of any one's coming in contact with this circuit is very remote.

The condenser-bushing potential device is relatively inexpensive and can be applied at a nominal cost for either one or two breakers.

In regard to Mr. Belt's comments I should like to point out that the insulation of the plug tap to the bushing, for impulse voltages is as good as the insulation of the bushing itself. Thus the insulating qualities of the bushing are in no wise impaired by the addition of the tap and therefore no more trouble due to impulse voltages will be experienced in the future than in the past.

In regard to the 6 per cent increase in stress on the upper portion of the bushing when the gap is discharging, I should like to emphasize the fact that the discharge of the gap is not an arc but a glow. For this reason the gap acts not as a short circuit but as an overflow to excess voltages. Hence the increase in voltage stress is not 6 per cent but lower—approaching 6 per cent as a maximum. The factor of safety of the bushing is great enough to allow this overvoltage indefinitely. Therefore the danger to the bushing caused by the almost infinitesimal time duration of an impulse is very slight.

The same gap-discharge characteristic mentioned above prevents sufficient loss of potential to influence relay operation during impulse flashovers even if they were of sufficient time interval which is unlikely. Tests made since the writing of the paper have shown that the secondary voltage drops only a few per cent, thus substantiating the fact that the normal primary voltage is maintained practically constant during disturbances. Repeated tests also demonstrate that the gap operation is automatic in that, when an impulse or surge "passes over," the gap ceases to function. It operates only in case of overvoltage and tends to hold the primary voltage at normal value.

Temperature variations of the condenser-bushing device are taken up in detail in the original paper. The effects are so small as to be negligible on most applications of the device.

All of the above is confirmed by field experience which has demonstrated satisfactory operation of this device in service, and its inherent automatic compensation for overvoltage conditions. The following points may be considered as being of especial importance from the standpoint of installation and operation. The apparatus is entirely self-contained. The 4000-volt circuit is short, thoroughly insulated and protected from mechanical injury or accidental contact by grounded metal housings. No other circuits have a voltage in excess of approximately 110 volts. There is no rotating apparatus of any kind used. There is no apparatus used which is subject to deterioration. In short, the initial installation and the succeeding apparatus is on a par with that of a standard low-voltage instrument transformer.

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[1] L. N. Crichton and H. C. Graves, Jr., TRANS. A. I. E. E., 1928, Vol. 47, No. 1, p. 259.

# Metallic Arc Welding Electrodes

## A Study of the Effects of Surface Materials

BY J. B. GREEN[1]
Non-member

***Synopsis.**—To understand the effect of surface materials on metallic arc welding electrodes, something must be known as regards the fundamental theory of arc heat distribution, arc vapor resistance, and similar matters which are modified by the presence of surface materials. The character of the arc may be changed by chemical and structural variations in the surface materials. Stability is one such arc characteristic.*

*Two types of stability are recognized,—chemical and electrical. Surface materials have a significant influence on the brittleness or ductility of weld metal. They also can be used to control the arc type, four such types being recognized. The influence of surface materials on the heating of electrodes is another phase of the matter of practical significance. Surface materials may be employed to control both the operating characteristics of the electrode and the resultant weld properties. Among the operating characteristics might be mentioned stability and rate of melting. Among the weld properties are included freedomf rom blow-holes and tensile strength. These and other practical applications of a comprehensive knowledge of surface materials are cited in this paper.*

* * * * *

BEFORE the effects produced by surface materials on metallic arc welding electrodes, can be understood, some familiarity with the arc itself must be gained, and an understanding of many of the fundamentals of welding acquired. Much of the subject matter presented is still in the controversial stage of development, but, to avoid numerous modifying remarks throughout the discussion, all reference will be assumed for the time being to be fact.

The arc itself appears to be a double thermocouple, the two couples being the junctions of the electrode tips with the opposite ends of the arc vapor stream. In Fig. 1 the welding arc is shown with the direction of thermocouple voltages common in mild steel welding indicated by arrows. The work is usually connected to the positive terminal of the welding generator. A voltage rise takes place at the filler rod end of the arc stream, the heat energy of the arc being changed to electrical energy while at the deposit end, the welding current suffers a corresponding voltage drop, electrical energy being changed to heat. There are eight possible combinations of thermocouple voltage directions and welding current directions. These are shown in Fig. 2, the eight combinations resulting from the possibility of running the welding current in either direction.

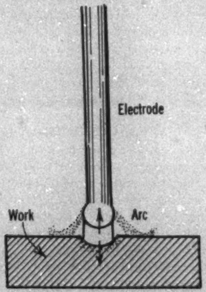

FIG. 1—THE METALLIC ARC SHOWING BY ARROWS THE DIRECTION OF THE THERMOCOUPLE VOLTAGES MOST COMMON IN MILD STEEL WELDING.

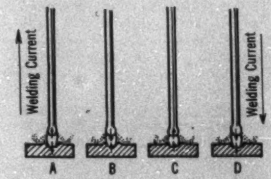

FIG. 2—THE FOUR POSSIBLE COMBINATIONS OF ARC THERMOCOUPLE VOLTAGE WITH THE TWO POSSIBLE DIRECTIONS OF WELDING CURRENT.

Two possibilities of varying the character of the arc are presented by this theory of arc heat distribution. One is the variation of directions of the thermocouple and impressed welding current combination, and the other is the e. m. f. of the thermocouples and impressed current.

The resistance of the arc vapor has little effect on arc heat distribution but it practically controls the total arc heat. Besides the arc vapor resistance, considered as a whole, the relative resistance of the core and sheath of the arc stream affect the character of the arc.

In studying both the total heat and its distribution in the metallic arc in connection with welding, two phases of the subject must be considered,—weld properties and operating characteristics. To bring the matter of these two phases under control the electrode designer makes use of varying combinations involving the four fundamentals of design. These are chemical composition and structure of the filler rod itself together with the chemical composition and structure of the surface materials.

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[1] President, Fusion Welding Corporation, Chicago.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Feb. 13-17, 1928.*

Heat is not the only factor to be studied. The electrical energy supplied by the welding generator is also converted into magnetic energy and light energy. Chemical energy, mechanical energy, and other forms are also resultants. The metallic arc and arc welding are so complex that to try to grasp all the variables and their interrelations as a whole baffles even the best trained scientific mind. For an understanding it is necessary to analyze and synthesize until the field has been covered, always remembering that the maintenance of the arc depends on the equilibrium of many variables, the change of any one usually resulting in a compensating shift of all the others. This is true not only of the arc but of the whole welding operation. These remarks are introduced to indicate that within the scope of a discussion confined essentially to the effect of surface materials on metallic arc welding electrodes completeness is impossible.

These surface materials fundamentally may vary chemically or structurally. Chemically, their variation is almost infinite, and structurally they may be coarsely or finely powdered or may be fibrous; they may be crystalline or amorphous; they may be applied evenly or unevenly, more on one side than the other, more at one end than the other or in single or multiple layers. Also, the relative mass of surface to electrode material may be varied. This relative mass has given rise to five classes of coatings. From the lightest to the heaviest they are commonly designated as the "inappreciable" coatings of Elliott, the residual coatings of Churchward, the surfacing of the author, the flux coatings of Hollup and Holslag, and the slag coatings of Kjellberg and Jones. All except the extremes are in quite general commercial use in this country, while the slag coatings seem preferred in Europe where alternating current is in common use for welding.

Taking up first the chemistry of the surface materials, it is found that both the arc heat distribution and total arc heat may be influenced through this fundamental. The electrodes themselves are metallic; hence they are first-class electrical conductors. The surface materials are most commonly non-metallic and are therefore second-class conductors. When the vapor of a second-class conductor predominates in the arc stream, the higher the temperature, the lower the resistance. This state of affairs tends to increase arc stability, since a given variation in arc length produces a lesser variation in resistance. The arc is complex and most observed tendencies are usually the algebraic sum of several tendencies. For example, an absolutely clean iron electrode operates with greatest stability when made the positive terminal of a d-c. generator because the thermo-couple action is such that the preponderance of heat appears at the negative end of the arc stream. By applying an "inappreciable" coating of calcium hydroxide, this thermocouple action is reversed and the arc becomes less stable, although the surface material is a second class conductor. Reverse the direction of the welding current and the stability is restored. Increase the quantity of the calcium hydroxide and the stability increases until the arc stream becomes saturated with the resultant vapor, after which further increase of stability ceases regardless of additions of the surface materials.

A welding rod was prepared to show the significance of surface materials as just indicated. The bottom or starting end of this electrode possessed no surface materials, the center had the residual wire-mill lubricants, which became essentially calcium carbonate by the time the electrode was used, and the top coated with the usual commercial flux composed of calcium carbonate together with siliceous materials. As such an electrode is run with direct current, (regular polarity), the first third gives a very unstable arc, the middle third, an arc which is commercially acceptable, and the top third, a very stable arc. All this seems due to a combination of arc heat distribution and arc vapor resistance.

To better understand the effect of surface materials on arc stability something must be said of stability itself. This matter is quite complex, but broadly, there is electrical and chemical stability. As the arc length increases, its resistance goes up, the arc voltage rises and the current falls. It is inherently unstable. Therefore ballast resistance must be introduced in a constant potential source of supply current, or other stabilizing means be provided in a variable potential supply. Rasch has developed the equation for stability with a constant potential supply and the equation also applies at any one instant with variable voltage supply. This equation is

$$S = \frac{E_0}{I} - \frac{K_s L}{I^2}$$

where

$S$ = What might be called "Stability Units."

$E_0$ = Overvoltage or generator voltage minus arc voltage. It is the voltage required to force the current through the ballast resistance.

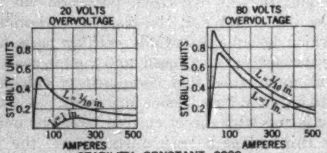
$I$ = Current in amperes flowing in the welding circuit.

$L$ = Arc length in inches.

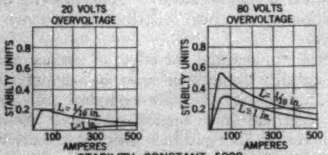
$K_s$ = A constant of the electrode called "Stability Constant."

In Fig. 3, it is plotted for extreme values of the constants as they appear in welding. It will be noted that as the current increases, a variation in the constants has little effect on the stability, all curves falling between 0.1 and 0.2 stability units at 500 amperes.

Chemical stability is no doubt due to violent chemical reactions taking place in the arc, usually between the electrode materials and surrounding atmosphere. It is well known that as the current is increased from zero, the arc is at first silent, then the voltage drops, making a volt—ampere curve of seemingly hyperbolic form. This is shown in Fig. 4 from $A$ to $B$. At $B$ it drops suddenly and continues on in much the same form from $B^1$ to $C^1$. The arc, after passing the critical point $B$, hisses. This drop appears to be due to the introduction of the vapor of a second-class conductor a product of chemical reaction, and this same chemical reaction produces the "hiss." If a hissing arc is surrounded with a chemically inert atmosphere, the hiss ceases and the arc voltage rises to values indicated on the line $B$-$C$.



STABILITY CONSTANT 2000



STABILITY CONSTANT 5000

FIG. 3—RASCH'S EQUATION FOR STABILITY PLOTTED AS CURVES, USING EXTREME VALUES OF ARC LENGTH, BALLAST RESISTANCE, AND STABILITY CONSTANT

Most surface materials affect the stability constant of the electrode because they are vaporized and enter the arc stream. In this manner they affect the electrical stability of the arc according to Rasch's equation. In Fig. 5, is shown a picture of the welding arc taken with infra-red light showing three stages of the transfer of a single drop of metal in the metallic welding arc. In taking these photographs and others shown in this paper, a light filter was interposed between the arc and the plate, and this allowed substantially infra-red light only to reach the plate. At the left, in Fig. 5 the drop has reached maximum size and is about ready to capillary across to the deposit. Note that the drop is almost completely surrounded by the arc flame and, just prior, it was so surrounded. In the center, the drop has just touched the deposit metal. Note that the flame has disappeared and that a white hot, but still solid, collar is left on the end of the electrode. At the right the drop is about to neck off re-establishing the arc. The collar is still in evidence. This collar quite evidently represents the material receiving maximum contact with the surrounding atmosphere while at temperatures most apt to combine with the oxygen and nitrogen. An inert surface material which is fluid and tends to wet this white hot collar obviously protects it from contact with the surrounding atmosphere. Thorium oxide is such a material and a mild steel electrode coated with it gives an arc practically as slient as that between carbons.

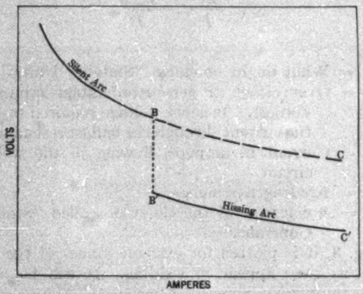


FIG. 4—VOLT-AMPERE CURVES OF THE "HISSING" AND "SILENT" ARCS

FIG. 5—THREE STAGES OF THE TRANSFER OF A SINGLE DROP OF MOLTEN METAL AS IT TAKES PLACE IN METALLIC ARC WELDING

In Fig. 6 this arc is shown at the left. Note the large size of the drop as compared with the one at the center from the same electrode uncoated. The electrode with thorium oxide permits the drop to form without being literally blown off before reaching maximum size by violent chemical action. At the right is an arc from the same electrode coated with beryllium oxide. Note that this is smaller than that from the uncoated electrode at the center. The chemical action seems more violent and the drops are detached very rapidly. Each of these views was selected from several thousand pictures taken as representing the largest drop in each case.

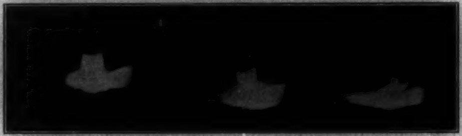


FIG. 6—ARCS WITH THREE TYPES OF ELECTRONS
Left coated with thorium oxide
Center uncoated
Right coated with beryllium oxide

These pictures lead to a few remarks on arc types, all of which may be produced by surface materials.

At any certain current, every electrode tends to give some one of the four recognizable arc types. The one at the left is a steady core type while the one at the right is a sheath type; the hollow center of which cannot well be represented by photography. In the steady core type the arc tends to pull off the bottom center evading the upper edge of the drop. In Fig. 7 the reverse is true, an erratic core type arc being shown which tends to pull off only from the upper edge of the drop. This is a very difficult arc for the welder to handle. A saturated arc is shown in Fig. 8, the arc stream pulling off from the entire cross-section of the electrode. This is probably the most satisfactory arc for the welder to handle. The sheath type is probably a special form of the erratic core type, or vice versa, the arc merely pulling off from all points of the upper edge of the drop at once. This leads to the conclusion that the different arc types are the resultant of the absolute resistance of the arc vapor stream and the relative resistance as between the central and outer portions. A steady core type arc often may be changed to a saturated type by merely increasing the current density. Some electrodes melt in their entirety on account of resistance heating before the current density is raised to the point that a saturated arc results.

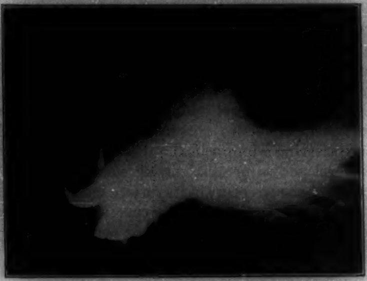


Fig. 7—Erratic Core Type Arc

Fig. 8—Saturated Type Arc

The influence of surface materials on the heating of electrodes is another phase of the matter of practical significance. Most electrode heating is due to poor holder contact and so perfect contact must be assured in studying the effect of surface materials themselves in this respect. In Fig. 9 are shown the curves obtained by allowing the same electrode to reach equilibrium temperatures in the air at various currents, the surface only being varied for each curve. It will be noted that less current is required to heat what is known as a bare electrode as shown in Curve *A*, possessing only the residual wire mill lubricants as a coating, than the heavier coated Green Surface shown in Curve *B*, or the polished rod shown in Curve *C* which is free from all surface materials. Conversely, the Green Surface and polished rods will carry higher welding currents than the so-called bare finish.

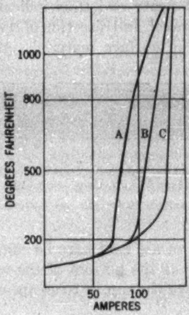


Fig. 9—Effect of Electrode Surface

A. Bare
B. Green surfaced
C. Polished

To most people the practical application of all this fundamental theory is the interesting thing. Both operating characteristics and weld properties may be controlled through the intelligent employment of surface materials applied to metallic arc welding electrodes. Possession of the handbook data on the subject permits deliberately designing an electrode for a specific purpose. Not many years ago, electrodes were developed by hit and miss experimenting and a use found for them after they were developed. Handbook data cannot very well be developed without a knowledge of the fundamental theory. It would be like trying to design structural members without a knowledge of moment of inertia, for example, which requires calculus to compute. For obvious reasons, most of the electrode designer's handbook data of which the author has knowledge must, for the time being, be kept a trade secret of the research laboratory of the company where it originated. No attempt, therefore, will be made to be specific or give reasons, but merely a few of the practical applications involving surface materials on welding electrodes will be cited.

One of the earliest applications was in Europe where alternating current is largely used for welding. The bare electrode seldom gives sufficient stability for a-c. welding as a commercial process and so slag or flux coated electrodes were developed. The welding of mild steel has become a production process subject to all the competition of other such processes. The electrode, therefore, must exactly fit the job. Every different set-up represents a different set of conditions to be met. Sometimes quality is involved. The weld must be free from blow-holes. These are the result of a race between the escaping gas and the solidifying metal in which the gas loses and is imprisoned in the weld. Fig. 10 shows the blow-holes in a piece of stainless steel. Such steel offers a splendid opportunity to study the subject of blow-holes because they are generally elongate and thus indicate their origin, their extent of travel, and direction of travel. Through the proper use of surface materials on the electrode the distribution of arc heat may be controlled and the blow-holes held at the bottom of the weld allowed to reach the center or the top, or to escape entirely leaving a sound weld.

Fig. 10—Longitudinal Cross-Section of a Chromium Steel Metallic Arc Weld Deposit used to Study Blow-Holes in Welds

The significance of blow-hole control through the use of surface materials is indicated in the report of a 46-mi. all metallic arc welded pipe line. The coated electrodes which happened to be developed in the author's laboratory were used for welding the 46 miles. When completed, the entire line was tested at 650 lb. per sq. in. pressure without showing a single blow hole leak.

Often oxides and nitrides are found in arc welds representing a content of 1 per cent in mild steel, while all other elements, other than iron, are not over ½ per cent. Thus in determining the physical properties of the weld in so far as such properties depend on the chemical analysis of the deposited metal, these oxides and nitrides are often the predominating factor. Surface materials may be used to protect the transferred metal so that the brittleness incident to the presence of oxides and nitrides is reduced or eliminated.

Again, competition may demand that welds be made at high rates of speed. For example, ½-in. plate welding has been done by beveling the edges and running three layers of weld metal, usually brushing and often caulking each layer as laid. For the highest quality work of this sort, three feet per hour per operator is good practise. By using the surfaced electrode developed in the author's laboratory, which alters the arc heat distribution, sound welds fuzing clear through a ½-in. plate have been made at a rate of over 20 ft. per hour on plates butted together without beveling and with one passage of the electrode.

Some feats which are at least impractical in any other way may be accomplished through the use of surface materials on electrodes. For example, safes and vaults are often lined with stainless steel because the oxygen cutting torch will not successfully cut it. In forming stainless steel into tanks and other articles it becomes desirable to cut it, (say, for a manhole), where shearing is impractical. The author's laboratory has developed a metallic cutting electrode which, on account of the structure of its surface materials, readily cuts stainless steels. It also cuts and welds under many extreme conditions. It has even been used to lay down a weld deposit under water.

These are only a few out of the very many practical applications of a knowledge of surface materials on metallic arc electrodes. Furthermore, the effect of surface materials is only one consideration of arc welding. Metallic arc phenomena are extremely complex and when used for welding, the complexity is tremendously increased. Knowledge of the subject is very far from complete and probably the greatest opportunity for future fundamental research lies in discovering adequate means for measuring the arc thermocouple voltages.

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## Discussion

(Editor's Note: The following discussion by Mr. Green is in answer to questions asked after presentation of the paper. The questions are not repeated here.)

**J. B. Green:** The diameter of all the electrodes shown in the pictures was $^3/_{16}$ in. and we used a lower current value than would be considered proper in practical welding, about 125 or 150 amperes.

The low current was used to give slower melting of the electrodes so that the moving pictures could be taken more satisfactorily. If the currents had been different the pictures would probably be different. We were searching along broader lines. We were trying to find out, first, whether or not these four fundamentals had any effect at all, whether the chemical composition and structure of the rod and surface materials really did affect the welding rod. If we go into the subject still deeper such matters will certainly be taken into account.

Thorium oxide and berylium oxide were used as coatings but in practise those materials are too expensive and they are not suitable for other reasons. For example, thorium oxide will permit the production of an extreme example of a steady core-type arc. It protects the neck of the drop of molten metal from air contact. In those two respects it might be considered an excellent surface material for electrodes, but unfortunately it forms a very bad slag on the weld deposit. This is a coky slag which is very adherent and difficult to remove in the case of multiple-layer welding. The thorium oxide used for these experiments costs $48 a pound which would prohibit its commercial use.

For these pictures we have endeavored to use extreme cases, not picking necessarily the commercial case, but endeavoring to go as far as we could in any one direction.

The question was raised as to why the arc sometimes passed to the top of the puddle and sometimes to the bottom.

I have done a great deal of speculating on that point and up to the present have been unable to devise any experiments either to prove or disprove a hypothesis. I believe that to be a matter of relative, and what I might call absolute resistance of the arc stream. The relative resistance refers to the core and the sheath, if you can imagine the space between the electrode ends and the weld deposit as having a core and a sheath. If the core has a relatively high electrical resistance, the arc will pull off from the upper rim, because the outside sheath is of relatively low resistance. If there is not sufficient current flowing so that the arc can pull off from all points at once, it naturally will jump around from one point to another, forming the erratic core-type arc. However, if there is enough current flowing so that it pulls off all points at once, it forms a sheath-type arc. At any one current density, it might form either an erratic core-type or a sheath-type, depending on the absolute resistance of the vapor.

All of these pictures are of hand welding. We didn't find the automatic welding so favorable for taking these pictures. It may be we didn't have the proper control devices.

The same source of current was used for all the pictures, a constant-potential source with a large excess of ballast resistance.

Fluxes used in gas welding, I think, are employed very largely to dissolve the oxide, while in electric welding (and this is more or less my theory) I believe that they protect the welding rod from air contact and therefore formation of embrittling oxides and nitrides, but they have also another function, and that is the distribution of heat. I think in metallic arc welding the solution of the oxides is probably their least function.

**E. Herzog:** (by letter) Mr. Green has done pioneering work of great importance in his arc photographs. In his theoretical work, however, the assumption of various thermocouple combinations requires further explanation. Thermocouples as usually defined in physics do not seem to be able to generate the voltages or convert the quantities of energy appearing in the arc, even at arc temperatures. Can Mr. Green explain just why he has cast overboard all accepted explanations of arc phenomena in favor of his theory?

**J. B. Green:** Mr. Herzog refers to accepted explanations of arc phenomena, which I infer he feels apply to arc-heat distribution, and asks why I have cast these explanations overboard. While probably I am familiar with much of the explanatory matter which has been published concerning arc phenomena as it relates to arc-heat distribution, I do not know that this has been accepted. Furthermore, I did not intend to leave the impression that I have cast overboard these explanations. My thermocouple theory of arc-heat distribution is merely an effort to add another explanation and, if possible, make it more rational. From the days of the classic investigation of Hertha Ayrton, investigators have observed arc phenomena which could be interpreted as voltage drop or elevation at the arc terminals. The theory of thermocouple action seems to be a rational explanation of these voltage changes, except on one count, and that is the apparent magnitude of the voltage change. It is an established fact that the voltage change occurring in thermocouples composed of solid metals is quite small. In the metallic arc, new conditions are introduced. The junctions are between molten metal and a vapor. Usually they are also operating at extremely high temperatures. Until someone actually measures the thermocouple voltages in the metallic arc, who can tell just what effect these factors have on the action? My attitude towards my own thermocouple theory is neither to accept nor reject it until someone has actually measured the voltage changes.

My theory has been deduced by reasoning from incomplete experimental data but, so far as I know, the same applies to all other theories covering the same subject. I am inclined to the opinion that when the matter is completely worked out and proved, the theories previously advanced will be found useful in explaining all thermocouple action, while thermocouple action itself will be found to be the true explanation of arc-heat distribution.

# The Stability of the Welding Arc

BY P. ALEXANDER*

Member, A. I. E. E.

***Synopsis.***—*The stability of the iron welding arc is influenced by a number of factors, such as the nature and the aerodynamic state of the surrounding atmosphere, the strength and distribution of the magnetic field, the composition of the electrode, the nature and the amount of gases occluded in the electrode, etc. In this paper, however, only the first item has been discussed in an attempt to show that the cooling of the electrode and the arc core by dissociation of the surrounding gas has the preponderent influence on the stability of the arc.*

* * * * *

### INTRODUCTION

THE term "stability" of the welding arc can be interpreted in various ways and in accordance with conditions under which the welding arc is used.

In this paper, only one phase of this problem is discussed, namely, the influence of the various gases on the arc conduction of the current and on the voltage necessary to maintain the arc. The stability of the arc is judged here by the average voltage drop across the short iron welding arc.

### ARC CONDUCTION

The metallic welding arc is a combination of two factors, distinct, yet dependent upon one another. The conduction of the electric current is one factor and the transfer of the material across the arc stream is another factor. Both these factors are greatly influenced by the gas surrounding the arc. The first factor, perhaps, is more directly affected; therefore, only the first one will be discussed in this paper.

It is a well established fact that the conduction of the electric current in the arc is an ionic phenomenon. At any instant in a given volume of the arc core, there is about an equal number of electrons and positive ions. These carriers of the electric charges travel under the influence of the electrostatic field in opposite directions. The electrons migrate towards the anode, while the positive massive ions bombard the surface of the cathode spot.

It is this bombardment by the positive ions that keeps the temperature of the cathode sufficiently high to permit the thermionic emission of the electrons.

Since the electrons are moving at a much higher velocity than the positive ions, the relative number of these carriers is not the same. The number of electrons greatly exceeds the number of positive ions passed through the arc in a unit of time, so that practically the total current is carried by the electrons.[1] Yet without the continual production of the positive ions, the arc phenomena would be impossible; hence both factors play equally important roles and any condition affecting one of these factors (or both at the same time) will have great influence on the stability of the arc.

### THERMIONIC EMISSION OF ELECTRONS FROM THE CATHODE

The first factor,—that is, the thermionic emission of the electrons from the cathode,—is a function of temperature and is expressed by the well-known Richardson's formula† $I = A\,\theta^{\frac{1}{2}}\,\epsilon^{-\frac{Q}{2\theta}}$. The temperature is the first and the most important factor.

The second factor is the nature of the material of the cathode. Various substances at the same temperature will emit very different electronic currents. Among the substances giving the largest thermionic emissions, calcium oxide holds a marked place. If calcium oxide be present in sufficient amount on the surface of the electrode of a vacuum tube the thermionic emission may increase several hundred times over that produced by an electrode made, for example, of pure iron. In the case of the arc conduction of the current, it can be expected that CaO present on the surface of the electrode will also greatly facilitate the maintenance of a stable arc.

The third factor affecting the thermionic emission from the cathode is the gas surrounding the cathode. Various gases influence this emission to different degrees. The gas that has the most marked effect is hydrogen. Owing to its strong electropositive nature the first gaseous layer next to the cathode creates such a steep potential gradient, that the electrons will escape the surface of the cathode with great facility.

Taking, again, the example of calcium oxide, it is established that the thermionic emission from that compound surrounded with hydrogen increases very considerably. The thermionic current from incan-

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[1] For numerical references see bibliography.

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†. $I = A\,\theta^{\frac{1}{2}}\,\epsilon^{-\frac{Q}{2\theta}}$ represents the general law of thermionic emission and is applicable to the various substances.

$I$ represents current in amperes

$\theta$ represents absolute temperature which is given by $\theta = 273 +$ deg. cent.

$\epsilon$ represents 2.718

$A$ and $Q$ are constants which have various values for different substances. Thus for thermionic emission in air at low pressure:

| Substance | $Q$ | $A$ |
|---|---|---|
| Platinum...... | $131 \times 10^3$ | $6.9 \times 10^7$ |
| Carbon........ | $196 \times 10^3$ | $10^{15}$ |
| Sodium........ | $63 \times 10^3$ | $10^9$ |
| Baryta........ | $83 \times 10^3$ | $7 \times 10^7$ |
| Lime.......... | $80 \times 10^3$ | $5 \times 10^7$ |
| Magnesia...... | $79 \times 10^3$ | 4 |

descent calcium oxide in air at low pressure is 0.05 amperes per sq. cm. If hydrogen replaces the atmospheric gases, the thermionic current at the same temperature will be 1000 amperes per sq. cm. of the cathode spot. Even a trace of hydrogen is sufficient to increase the thermionic emission.

### IONIZATION

Passing now to the consideration of ionization, the first factor to be analyzed is the ionizing potentials of the materials present in the state of gas or vapor in the space between the electrodes.

The ionizing potential expressed in equivalent volts is the potential through which the electron must fall to acquire a sufficient energy to ionize the gaseous atom or molecule. The amount of energy necessary to produce this effect is proportional to the stability of the atomic structure. Since the helium atom possesses the most stable atomic structure, the ionizing potential for that gas is the highest. After helium comes neon, and so on, until calcium, and finally caesium (which requires the least energy for ionization) is reached.

TABLE I
TABLE OF IONIZING POTENTIALS[3]

| Name | Atomic number | Symbol | Ionizing potentials volts |
|---|---|---|---|
| Helium | 2 | He | 24.5 |
| Neon | 10 | Ne | 21.5 |
| Argon | 18 | A | 15.3 |
| Oxygen | 8 | O | 13.56–(15.5) |
| Hydrogen | 1 | H | 13.53–(15.9) |
| Phosphorus | 15 | P | (13.3) |
| Nitrogen | 7 | N | 10.8–(16.9) |
| Mercury | 80 | Hg | 10.39 |
| Sulphur | 16 | S | (10.31) |
| Zinc | 30 | Zn | 9.35 |
| Silicon | 14 | Si | 8.50 |
| Copper | 29 | Cu | 7.69 |
| Silver | 47 | Ag | 7.54 |
| Iron | 26 | Fe | 7.4 |
| Manganese | 25 | Mn | 7.4 |
| Lead | 82 | Pb | 7.39 |
| Molybdenum | 42 | Mo | 7.1 |
| Chromium | 24 | Cr | 6.7 |
| Titanium | 22 | Ti | 6.5 |
| Calcium | 20 | Ca | 6.09 |
| Aluminum | 13 | Al | 5.96 |
| Barium | 56 | Ba | 5.19 |
| Sodium | 11 | Na | 5.12 |
| Potassium | 19 | K | 4.10 |
| Caesium | 55 | Cs | 3.90 |
| Acetylene |  | $C_2H_2$ | (12.3) |
| Carbon Monoxide |  | CO | (14.3) |
| Carbon Dioxide |  | $CO_2$ | (14.3) |

NOTE: Values in parentheses refer to molecules.

From examination of Table I it may be concluded that if the vapors of alkaline earths or alkali metals be present in the space between the electrodes striking and maintaining the arc would be much easier than in air. The voltage required to strike the arc and the voltage across the established arc will be lower. This conclusion is quite in accord with the experimental data.[4]

From Table I it may also be seen that the ionizing potentials of certain monatomic gases are very much higher than those of molecular gases. Helium, for instance, has the highest ionizing potential—namely, 24.5 volts—whereas the ionizing potential of nitrogen is only 16.9 volts.

At first glance it would seem to be much easier to strike and maintain the welding arc in nitrogen than in helium; yet experiments indicate that the contrary is true; in fact, it requires much lower open-circuit voltage to strike the arc in helium than in nitrogen. With certain precautions, 20 volts are sufficient to strike the arc in helium, whereas at least 30 volts are necessary to strike the arc in nitrogen.[5]

This apparent paradox can be explained by the fact that in monatomic gases the electron impacts below the ionizing or radiating potentials are elastic. In helium, for instance, the electron impacts below 20 volts (minimum radiating potential) are elastic. The electron does not lose its energy at the first or second collision, but rebounds and proceeds in a zigzag course until it falls through the potential giving it sufficient energy to bring the helium atom into an excited state at the next impact. If an excited atom which already had absorbed 20 volts is again hit with an electron of sufficient energy, then the helium atom will be ionized.

This preservation of the energy of the bombarding electron during the successive impacts explains the possibility of drawing the arc in helium with lower open circuit voltage than in nitrogen.

In nitrogen as in all diatomic gases the electron impacts are not elastic. In that case the accumulation of energy by an electron falling through the potential should be fast enough so that in spite of continual losses during the encounter with the molecules, it will be able to acquire energy sufficient to ionize. Therefore the striking voltage in molecular gases must be considerably higher than in monatomic gases.

### COOLING OF THE ARC

The next factor affecting the ionization is the dissipation of energy and therefore the cooling of the crater and the arc core. It is a well established fact that it requires much greater voltage to strike the arc with water cooled electrodes than with electrodes allowed to become incandescent.[6]

The gases surrounding the electrodes and the arc core in certain cases cause such effective cooling that the arc voltage or the voltage necessary to strike the arc is very much higher. If the open-circuit voltage of the welding generator is not increased the arc becomes very unstable.

From an examination of the tables giving the physical constants of the gases, it may be seen that helium has the highest coefficient of heat conductivity: namely, 0.000339 calories per deg. cent. Yet the cooling effect of that gas on the arc is not greatly different than that of air of which the coefficient of heat conductivity is only one-sixth as great; namely, 0.0000568. On the other hand, if helium be compared with hydrogen, which has about the same coefficient of heat conductivity (0.000327) it will be found that the cooling effect of hydrogen is many times greater than that of helium. This indicates that the cooling effect of the gas is a function of some other much more powerful factor than the mere dissipation of heat by conduction.[7]

The well-known experiments conducted by Dr. Langmuir on heat losses from incandescent tungsten filaments placed in hydrogen established that the powerful cooling effect of that gas is due to the absorption of energy by dissociation at high temperature of the molecular hydrogen into the atomic state.[8] However, the mere fact of the dissociation of the molecules into the atomic state is not sufficient to produce the cooling effect. To produce that, the dissociation products should diffuse away from the arc core so that the recombination of the atoms into molecules with the inevitable restoration of the absorbed energy will occur at a sufficient distance from the arc core. Otherwise there will be an immediate restitution of the absorbed energy which excludes the possibility of the cooling effect. The most energetic cooling effect produced by hydrogen is due not only to the fact that the whole mass of that gas in the first gaseous layers next to the arc core is dissociated into atomic state, but also to the fact that the atomic hydrogen rapidly diffuses away from the arc core.

The most common gas met in welding is, of course, nitrogen, since it constitutes 78 per cent of the atmospheric air. This gas also dissociates into the atomic state in the first gaseous layers next to the arc core. The heat of dissociation of nitrogen is 274,000 calories per mol, that is, almost three times as great as that of hydrogen, (98,000 cal. per mol), so that it has the greatest capacity for absorbing energy from the arc. If the products of dissociation, that is, the atomic nitrogen, could be blown away from the arc in the same way as the atomic hydrogen is blown away from the arc, the atomic nitrogen would be three times as efficient a heat transmission medium as the atomic hydrogen. However, the dissociation of nitrogen into the atomic state does not begin until the temperature is 3500 deg. cent., whereas the dissociation of hydrogen is appreciable at 1800 deg. cent. A small percentage of nitrogen is dissociated in the first gaseous layer next to the arc core, but as soon as it leaves that region it recombines into the molecular state, with a complete restoration of the absorbed energy. Therefore the cooling effect of this reaction is neglible.

*Carbon monoxide* presents an interesting subject for study because, in spite of a very high heat of dissociation it is the gas in which the welding arc can be maintained with the greatest ease.

The heat of dissociation of carbon monoxide as calculated from the band spectra is 258,000 calories per mol.[9] If, in spite of this enormous heat of dissociation, this gas does not produce any appreciable cooling of the arc, it either is not dissociated by the arc or the products of dissociation cannot be blown off the arc, but recombine in the immediate vicinity of the arc core with full restoration of the absorbed energy.

For purposes of elucidation if possible on this interesting point, the writer made the following series of experiments:

After preparing and purifying a sufficient amount of carbon monoxide, a steam of that gas was passed as shown in Fig. 1 through a cylindrical clear fused quartz vessel in the middle of which were disposed two tungsten electrodes. The flow of the gas was adjusted so as to duplicate as nearly as possible the conditions of an actual welding operation, if such be made with carbon monoxide as a shielding gas. The out-flowing gas, after passing through a vessel filled with an aqueous solution of NaOH, was conducted to a quartz nozzle and burned in contact with the atmosphere. By bringing into contact and then withdrawing the tungsten electrodes, an arc of 30 amperes and 28 volts was established in the stream of gas for one minute. At the end of 60 sec. the arc was hardly visible through the black deposit on the inside walls of the vessel.

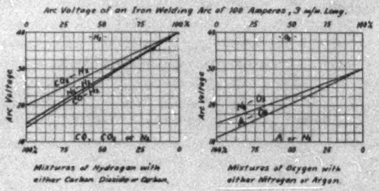

FIG. 1

The color of the flame of the outflowing gas was changed from the characteristic pale blue of carbon monoxide to yellow.

The following conclusions may be drawn from the above observations. Since the three known oxides of carbon—namely, CO, $CO_2$, and $C_2O_3$—are not solids at room temperature, the black deposit could be either pure carbon, a mixture of carbon and condensed tungsten vapor, or tungsten carbide. The chemical analysis of the deposit indicated, however, that the black deposit was carbon.

The experiments repeated with various mixtures of $H_2$ and CO indicated that the presence of $H_2$ does not prevent the formation of the black deposit. The dilution of CO merely reduces the amount of the deposit per unit time. However, when the experiment was repeated in pure argon, the walls of the vessel remained perfectly clear.

It may be concluded that carbon monoxide is dissociated by the arc and that one of the products of dissociation was diffused away.

This is an apparent contradiction to the well-known fact that the dissociation of carbon monoxide begins only at an extremely high temperature. Therefore, the gas should behave in this respect like nitrogen. This contradiction, however, is apparent only, since that reaction took place in the presence of readily oxidizable materials, and the heat of formation of the secondary reactions of the liberated oxygen (and probably a part of carbon) compensates for the cooling effect of the first reaction.

However, since the gas has a smoky appearance in the immediate vicinity of the arc core it may be inferred that the liberated carbon was condensed into the solid state in the region next to the arc core. Since the heat of sublimation of carbon is quite accurately known, it is possible to represent the above reaction by the equation:[01]

$$\text{C (gaseous)} = \text{C(solid)} + 141{,}000 \text{ calories}$$

so that even in the absence of other secondary reactions of oxidation and carburation of the electrodes, the condensation of carbon alone restores the greatest part of the energy previously absorbed from the arc core.

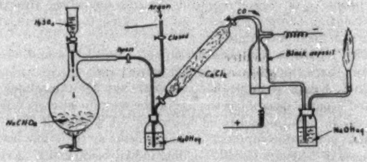

Fig. 2

The oxidation of tungsten, that is formation of $WO_2$ or $WO_3$ give respectively 131,400 and 196,300 calories per mol.

In the case of iron the formation of $Fe_2O_3$ or $Fe_3O_4$ produces 197,700 and 270,800 calories, respectively. In other words, the condensation of the gaseous carbon and the oxidation reaction supply an amount of heat almost sufficient to neutralize the cooling effect of the first reaction. The as yet unpublished results obtained by other experimentators, communicated to the writer, indicate that in the arc maintained in C O there are formed products of polymerization such as $C_xO_y$ or $(CO)_x$.

If this is correct, then the mechanism of dissociation of C O may be explained in a different way, namely, the products of polymerization diffuse away from the arc core without absorption of energy, and being unstable, break up in the cooler regions of the arc. This explanation of the mechanism of dissociation seems to the author to be the most plausible.

The most remarkable property of carbon monoxide is its stabilizing influence of the welding arc burning in any gas to which carbon monoxide is added in sufficient amount.

This property is quite astonishing because the ionizing potential of this gas is high; namely, 14.3 volts. This fact, however, can be reconciled with the stability of the arc in that gas, by observing that only a certain percentage will be dissociated. The rest of the gas will be in molecular form and that with regard to the ionization by successive electron impacts carbon monoxide behaves in an astonishingly similar manner to mercury vapor.[11] Owing to the existence of several critical potentials both these gases may accumulate the energy necessary for ionization by steps, and as in mercury vapor, so in carbon monoxide gas it is possible to maintain an arc with a very low voltage.

*Carbon dioxide gas* is dissociated in the arc into oxygen and carbon monoxide. A part of the produced carbon monoxide will undergo further dissociation into carbon and oxygen. However, in the presence of an excess of carbon dioxide, the amount of dissociated carbon monoxide will be very small.

The heat of dissociation of carbon dioxide into oxygen and carbon monoxide is 68,000 calories per mol. If the products of dissociation are blown off the arc, the arc will be always burning in carbon dioxide, which through its dissociation will produce a very strong cooling effect causing instability of the arc.

The voltage drop may be as high as 30-35 volts and the arc will be very unstable. If, however, the arc is maintained in a more or less stationary atmosphere of the dissociated carbon dioxide, it will be stable, and the arc voltage of an arc of say 175 amperes will be only 19 volts.

Fig. 2 shows the relationship between the composition of the gaseous atmosphere and the arc voltage at an iron welding arc of 100 amperes, three millimeters long.

## CONCLUSION

The stability of the iron welding arc is influenced by a number of factors, such as the nature and the aerodynamic state of the surrounding atmosphere, the strength and distribution of the magnetic field, the composition of the electrode, the nature and the amount of gases included in the electrode, etc. In this paper however, only the first item has been discussed in an attempt to show that the cooling of the electrode and the arc core has the preponderent influence on the stability of the arc.

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7. P. Alexander, *The Electric Arc*, Jl. A. I. E. E., Trans. Vol. 47, p. 334 1927.

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10. H. Kohn and M. Guckel, *Naturwiss* 12, (1924). p. 139.

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## Discussion

**Elihu Thomson:** The paper is one which sums up in a brief way the result of a lot of study that has been given to the subject by Mr. Alexander.

Mr. Alexander, of course, has made a great point of dissociation. Dissociation in the way that he deals with it means simply that a molecule by the delivery of electric energy is broken up into atoms. He deals with hydrogen dissociation, which forms the basis of the Langmuir atomic-hydrogen process of welding, where an arc is formed and is fed with hydrogen, which passing through the arc is dissociated into atomic hydrogen. Consequently, the process is called the atomic-hydrogen method. It is known that a very large amount of energy is required to separate hydrogen from hydrogen, and as the atoms leave the arc and the gas falls in temperature slightly they recombine and there is enormous restoration of the energy which was demanded to dissociate them.

Mr. Alexander deals with such a process and applies it to other gases and compounds. Let us take the case of carbon monoxide. Carbon monoxide, as he shows, requires for its dissociation a large amount of energy. This would indicate rather high voltage in the arc. But he also studies it in this way. Does the energy come back, and where does it come back? It comes back at once close to the locus of dissociation. He shows that the gases do not diffuse away, and calls attention to that property of carbon itself, which being vaporized, is immediately condensed into the solid form, in the form of what we might call "soot," if we could see it. He shows that in the condensation of the vaporized carbon we have also an enormous output of energy. The carbon might be visible, if we could separate it from the oxygen, but the oxygen dissociated from the carbon monoxide is there to recombine, and it also represents a store of energy given out when it recombines with the carbon. Mr. Alexander so accounts for the properties of the carbon-monixide arc, which has been found to be one of the best stabilizers for arcs drawn in other gases. A mixture of carbon monoxide with hydrogen, for example, gives an excellently stabilized arc as compared with what you would get with hydrogen alone.

**Eugene Herzog:** It is only in one minor point that I feel obliged to disagree with the author, *i.e.*, in his application of Langmuir's dissociation theory to carbon monoxide. It does not seem logical to me to assume that the fact of no energy absorption would explain the stabilizing influence of carbon monoxide on the arc; a more active participation of carbon monoxide through easier ionization probably due to resonance potentials seems a necessary assumption. A hasty search of literature did not disclose the existence of any resonance potential, but data seem entirely lacking on the subject.

**P. Alexander:** Referring to Mr. Herzog's question, I will say that in Table I, I give the ionizing potentials not only of atoms but also of molecules. For instance, if we take oxygen, the ionizing potential of atomic oxygen is given as 13.56. When oxygen is in a molecular state it requires a slightly higher energy to ionize the molecule. The value given is 15.5. And so on. Most of the given values refer to the atoms, because when these elements are vaporized they are in an atomic state, not in a molecular state. The molecular state of these elements is not stable.

Undoubtedly certain molecules are what most of the physicists in this country call in an excited state. That is, they have already absorbed a certain amount of energy. Ionization of these excited molecules is easier, so that energy necessary for a bombarding electron to ionize them will be less.

The absence of absorption of energy does not explain the stabilizing properties of carbon monoxide. It explains only why in spite of the observed dissociation of a certain amount of carbon monoxide the arc core is not cooled by this reaction. In certain cases it may happen that the subsequent reactions of the dissociation products with other materials present in the arc may liberate more energy than the amount absorbed from the arc core. In such a case the arc core will be heated instead of cooled; thus the dissociation of one mol that is one gram-molecule of carbon monoxide absorbs 248,445 calories which can be expressed by the equation:

$$CO = C_g + O - 248{,}445 \text{ calories}$$

The ($C_g$) gaseous carbon condenses immediately into solid carbon thus:

$$C \text{ (gaseous)} = C \text{ (solid) plus } 141{,}000 \text{ calories}$$

Also the atomic oxygen recombines into molecular state with evolution of energy thus:

$$\tfrac{1}{2}(O + O) = \tfrac{1}{2} O_2 + 81{,}000 \text{ calories.}$$

And finally if the molecular oxygen combines with tungsten vapor that reaction will yield:

$$\tfrac{1}{2} W + \tfrac{1}{2} O_2 = \tfrac{1}{2} WO_2 + 65{,}700 \text{ calories}$$

so that the total amount of the liberated energy will be 141,000 + 81,000 + 65,700 which equals 287,700. However, the stabilizing property of carbon monoxide depends not on the absorption or evolution energy, but as I stated "owing to the existence of several critical potentials."

With regard to the literature on this subject, I would refer to the reference (11) given at the end of my paper.

**C. H. Keel:** I think that two years ago Mr. Alexander presented a paper describing the use of the metallic electric welding process in an atmosphere of hydrogen. I wonder if there has been as much development in that process as there has been in the case of tungsten electric welding in hydrogen, and if there are any practical limitations to that process.

**P. Alexander:** The development of the shielded-arc process is going on in our works, but as is the case with all the new processes it is not sufficient to establish the fundamental facts about the process before it is commercialized. It is necessary also to evolve the technic of handling that process. The present work which we are doing in our factories consists of the development of the technic.

We also find that there are certain limitations to the process. For certain work, this process is not suitable. We find that in other fields, unexpected fields, this process is very suitable and gives better results than we expected it would.

A. P. Wood, in his paper[1] tells of the application of this process to large generators.

**J. W. Sheffer:** Does the atomic-hydrogen process produce welds free from oxides?

**P. Alexander:** It does. The resistance to corrosion of atomic-hydrogen welds is not definitely ascertained as yet, but I believe that it should give higher resistance to corrosion than welds with oxides and other impurities.

Experimentally, atomic hydrogen was used on welding plates up to 2 in. thick, but in practical work I believe much lower thicknesses should be used. If you will notice, in the pamphlet issued by the General Electric Co., thicknesses up to ¼ in. only are recommended.

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[1] *Welding and Manufacture of Large Electrical Apparatus*, A. P. Wood, see p. 717.

# Arc-Welded Structures and Bridges

BY A. M. CANDY[1]
Member, A. I. E. E.

***Synopsis.****—The use of arc welding for constructing buildings, machinery, bridges, etc., has come into prominence during the past eighteen months, due to the merits of the process becoming recognized by a number of designers. Undoubtedly within the next few years the applications of the process will be extended rapidly as our available data are corroborated and amplified and as the limitations of the process become well defined.*

*The arc welding process of joining steel members to produce a fabricated structure, either to replace riveting or to take the place of castings, will produce results not obtainable in any other way known at present. Among the advantages of arc welding are the following:*

*1. The weight of materials required in a member or structure can be reduced by as much as 18 per cent.*

*2. No material is removed from members for welded connections such as rivet holes for riveted construction.*

*3. The weight of connecting material in some cases can be reduced 50 per cent to 90 per cent.*

*4. Absolute fixation of one member to another can be easily and economically obtained.*

*5. Continuity of members intersecting others can be readily obtained.*

*6. Greater rigidity can be obtained in a structure.*

*7. Overlapping members can be completely sealed by weld metal, thereby excluding moisture, preventing corrosion, and making a structure easier to paint.*

*8. Changes in or additions to structures can be made with a great saving in both time and expense.*

*9. More pleasing designs and in some cases, designs impossible by other processes, can be produced.*

*10. The welding process is practically noiseless.*

In the past when beams or columns were required of section greater than the largest commercial rolled shapes available, they were constructed of angles for flanges and stiffeners and a plate for a web as shown in Fig. 1. Today, by using the arc weld process, a similar beam can be made from plate material exclusively (See Fig. 2). The former girder weighs 798 lb., and carried a maximum central load of 68,900 lb. The latter weighed 18 per cent less, or 656 lb., and carried a maximum load 13 per cent greater, or 78,000 lb. The load deflection diagrams of these two girders are shown by Fig. 3, as 20 and 20-A, for riveted construction using angles and plates whereas 21 and 21-A are designed for welding using plate material only. This latter design was used for the large second floor girders in the Sharon arc welded building (Fig. 4.) These occurred in pairs over the crane runway illustrated in Fig. 5. These girders weighed 9 tons each, whereas girders made of angles for flanges and stiffeners for riveted design had an estimated weight of 11 tons which shows 18 per cent saving. Since there are 22 of these girders in the building, a total of 44 tons of steel is saved by the welded design.

For the first arc welded girder type railroad bridge, this same construction is used for the main side girders, each weighing 6 tons, (Fig. 6). This bridge has a span of 53 ft. 9 in. and is 62 ft. 4 in. long over all, requiring 20 tons of steel.

One of the advantages observed in the design and construction of this bridge was the ease of connecting the inside sketch stiffeners to the main girder webs and top faces of the floor beams as compared with the connection details which would be required for riveted construction.

The advantages of not punching holes in members for welded construction are almost too obvious to mention as indicated by the following example:

To show the advantages gained by simply substituting arc welding for riveting in tension members, two specimens were prepared as shown by Nos. 17 and 18 in Fig. 7. Specimen No. 17 comprises two angles 2½ in. by 2 in. by 3/16 in. by 4 ft. long with their 2½ in. legs located against two shank plates ¾ in. by 5 in. by 1 ft. long, with the angles overlapping the plate ends four inches. The heel and toe of each angle was welded along the 4-in. length and across the ends of each angle to the shank plates. Specimen No. 18 was slightly different in that the angles were 4 ft. 2½ in. long, overlapping the shank plates by 6½ in., and were riveted to the shank plates with 6 rivets of ⅝ in. diameter, power driven in 11/16 in. diameter holes.

The comparative failures of these specimens are shown by Fig. 8. The welded specimen first failed through the 2½-in. leg followed by tearing through the 2-in. leg adjacent to the end of the shank plates. The riveted specimen failed through the first rivet hole at the end of the shank plate.

The following tabulation gives the pertinent data:

| Specimen number | Lb. elastic limit | Lb. ultimate load | Ultimate load in lb. per sq. in. of sectional area of the 2 angles |
|---|---|---|---|
| 17 | 70,000 | 94,000 | 58,000 |
| 18 | 60,000 | 72,000 | 44,500 |

In addition to the fact that the welded specimen was more than 30 per cent stronger than the riveted specimen, it is interesting to note, in passing, that the elongation of the welded specimen was 168 per cent greater than the riveted specimen, the values being 1.12 in. over a length of 4 ft. 3½ in. for the riveted specimen,

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*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., Feb. 13-17, 1928.*

and 3 in. for the welded specimen measured over a length of 40 in.

The weight of connecting material for welded joints is very much less than for equivalent riveted connections. For example, the 9-in. *I*-beam, (Fig. 9), required only two pounds of weld metal to attach it to the columns and it withstood a maximum central load of 67,200 lb. In the case of the specimen, Fig. 10, the connecting angles and rivets weighed 22 lb. and the

Fig. 1—Riveted Girder

Girder 15 ft. long, 14-15/16 in. deep, weight 798 lb. Four flange angles 4 by 3 by 5/16 in. 16 web stiffener angles 3 by 2 by 1/4 in. 12 filler plates 2-1/2 by 5/16 in. and two 5 by 5/16 in. Web plate 14 in. by 5/16 in. Performance is shown in Fig. 3, curve No. 20.

Fig. 2—Arc-Welded Girder

Girder 15 ft. long, 14-3/4 in. deep, weight 656 lb. Two flange plates 10 in. by 3/8 in. 16 web stiffener plates 3 by 1/4 in. Web plate 14 by 5/16 in. Performance is shown in Fig. 3, curve No. 21.

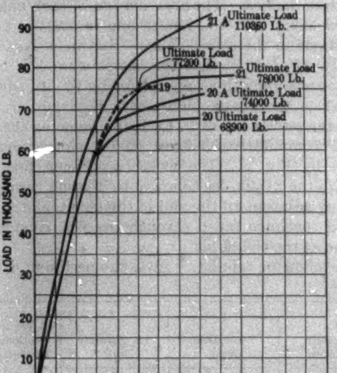

Fig. 3—Load-Deflection Curves of Riveted and Welded Girders Shown in Figs. 1 and 2

Curve 20A is a specimen duplicating the riveted girder in Fig. 1. Curve No. 19 is a specimen using identical material except that the connections were made with weld metal instead of rivets which reduced the weight of complete specimen to 785 lb. instead of 798 lb. Curve No. 21A is a specimen similar to arc-welded girder shown in Fig. 2, except that 4 additional web stiffener plates were used and all stiffeners were made 4-1/2 in. wide; also a top cover plate 9 in. by 5/16 in. by 6 ft. long was added, making the total weight 795 lb.

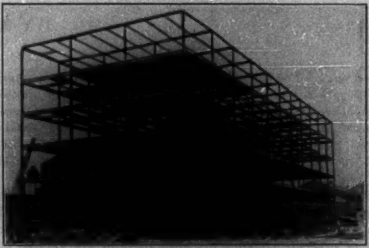

Fig. 4—Largest Arc-Welded Building Produced to Date

Five stories and mezzanine floor 70 ft. by 220 ft. by 80 ft. high, 790 tons of steel; saving 95 tons of steel since a riveted building of same design would require 885 tons of steel. Location, Sharon, Pa.

Fig. 5—View Down Crane Runway of 790-Ton Arc-Welded Building

Showing 9-ton girders made up of plate material, only saving 2 tons of steel as each would require 11 tons of steel for riveted construction.

Fig. 6—All Arc-Welded Railroad Bridge of Through-Girder Type

specimen carried only a central load of 58,700 lb. or 12½ per cent less capacity with 11 times the weight of connecting material.

The load deflection diagrams of these specimens are shown by Fig. 11 curves No. 8 and No. 9, respectively.

These same specimens illustrate the fact that complete fixation of the 9-in. *I*-beam to the column was obtained in case of the welded specimen as all failure was due to buckling of the beam top flange and crippling of the web. In the case of the riveted specimen the first failure was the bending of the top angles followed by

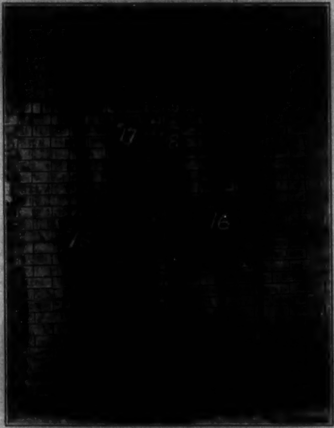

Fig. 7—Tension-Test Specimens Welded and Riveted

No. 17 is arc-welded. No. 18 is riveted. Deflection curves are shown in Fig. 8.

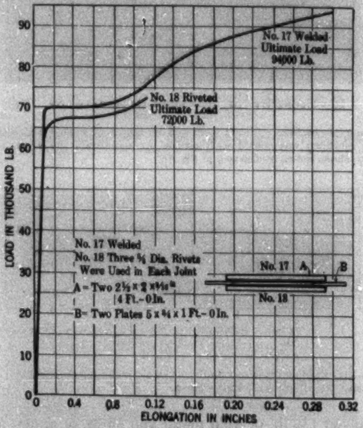

Fig. 8—Load-Deflection Curves of Specimens 17 and 18

The welded specimen No. 17 failed just outside the shank plate through the angles at 94,000 lb. and elongation of 3 in. on 3 ft-4in. centers. Riveted specimen No. 18 failed through first rivet hole at 72,000 lb. and elongation of only 1.12 in. on 4 ft. 3-1/2 in. centers.

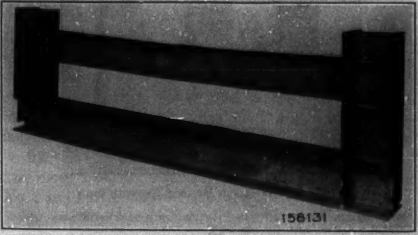

Fig. 9—Arc-Welded Beam

Beam member is a 9 in. 21.8 lb. 7 ft-11-3/8 in. long welded at ends to 10 in. H columns 49-1/2 lb. per foot. Performance shown by Fig. 9 curve No. 8.

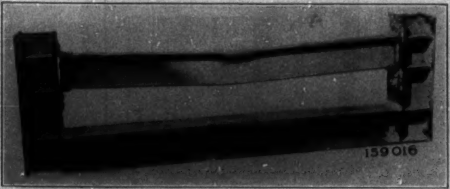

Fig. 10—Riveted Beam

Specimen same as shown in Fig. 6, except that beam is secured to column by 1/2 in. thick angles and 20 rivets 3/4 in. diameter. Performance shown by Fig. 9 curve No. 9.

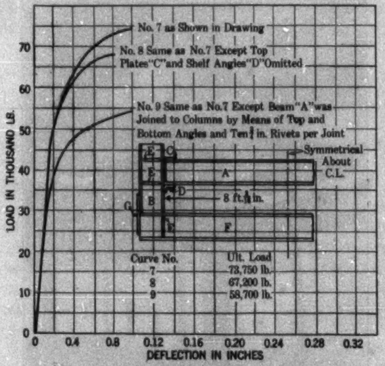

Fig. 11—Load-Deflection Curves of Beams in Figs. 7 and 8

Also Curve 7 shows a specimen similar to Fig. 7 except that seat angles *D* 4 in. by 3 in. by 3/8 in. by 5 in. long and top plates *C* 4 by 7/16 by 5 in. long were used as shown in sketch.

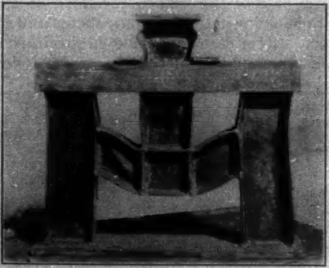

FIG. 12—WELDED BEAM CONSTRUCTION

Beam member 6 in. 1-12-1/2 lb. 18 in. long arc welded to columns. Beam deflected 3-5/8 in. with 100-ton load.

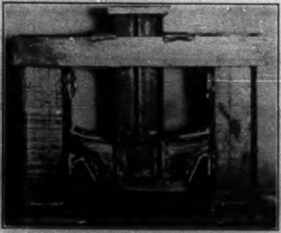

FIG. 13—RIVETED BEAM CONSTRUCTION

Beam member same as for Fig. 8 but secured to column by 1/2 in. angles and 32 rivets 5/8 in. diameter. Beam deflected 1 in. with 60-ton load when top angles failed.

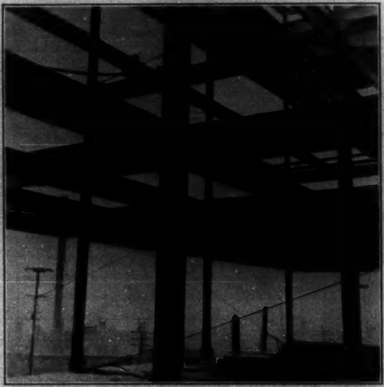

FIG. 14—TYPICAL COLUMN CONNECTIONS IN 790-TON ARC-WELDED SHARON BUILDING

Continuity of 20 in. 1.65 lb. header girders secured by plates in column just above the 15 in. I floor beams. Continuity at bottom of 20 in. I secured through seat angles under 15 in. I floor beams.

flange buckling and web crippling. These characteristics are shown possibly even better in Fig. 12, which specimen carried a maximum load of 100 tons whereas specimen Fig. 13 carried only 60 tons when the top angles failed. In these cases, the connecting material ratio is ten to one in favor of welded connections which involved 1½ lb. of weld metal and 15 lb. of angles and rivets, with improved performance for the welded structure.

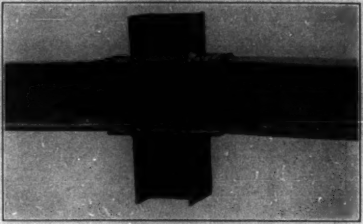

FIG. 15—WELDED BEAM CONSTRUCTION

Two cantilever 9 in. Bethlehem I-beams 20-1/2 lb. secured to 8 in. H column 32 lb. using seat angles 4 in. by 3 in. by 3/8 by 5 in. long, top reenforcing plates 4 in. by 1/2 in. by 4-1/2 in. long. Continuity plates, 3 in. by 5/8 in. by 6-5/8 in. long located in column, give the effect of making beams continuous through the column. Failure took place by crippling of beam webs. Performance shown in Fig. 13 Curve No. 2.

FIG. 16—CLOSE-UP OF SPECIMEN DUPLICATE OF FIG. 11

Shows stress lines on beam webs and no failure of welded connections. This specimen was coated with cement to accentuate the stress lines. Performance shown by Curve 2 of Fig. 13.

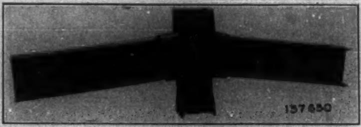

FIG. 17—SPECIMEN SIMILAR TO FIG. 11 EXCEPT CONTINUITY PLATES WERE OMITTED IN COLUMN

As a result of omitting continuity plates the column web buckled. Performance shown in Fig. 13 Curve No. 4.

The advantage of obtaining continuity of lines of beams or girders by welded connections lies in the fact

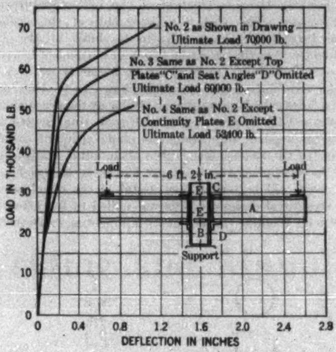

FIG. 18—LOAD-DEFLECTION CURVES OF SPECIMENS IN FIGS. 10 AND 12

**Also Curve 3 shows a specimen similar to Fig. 10 except that no seat angles or top reenforcing plates were used.**

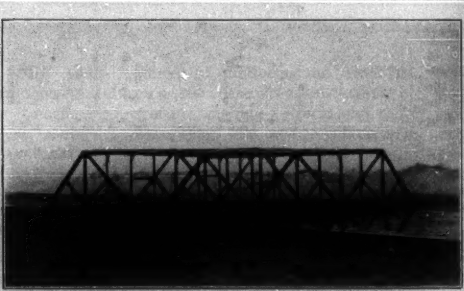

FIG. 19—FIRST TRUSS-TYPE ARC-WELDED RAILROAD BRIDGE AT CHICOPEE FALLS, MASS.

**Welded bridge uses 80 tons of steel. Riveted bridge design specified 120 tons of steel.**

FIG. 20—TWO BAYS BEING ADDED BY ARC WELDING TO A SMALL ARC-WELDED BUILDING

**Making structure 40 ft. by 100 ft. by 40 ft. to tops of columns. A saving of over 10 per cent was made compared with estimated riveted cost.**

that the designer can save weight in the structure. For example, in the 790-ton Sharon building, 51 tons of steel was saved by designing floor beams and header girders for continuity. The continuity of the girders through the columns was obtained by welding continuity plates in the columns in line with the top flanges of the girders as per Fig. 14. That this construction will produce continuity is illustrated by Figs. 15 and 16, which show failure by crippling of the *I*-beam web without any sign of weld failure whereas if the plates in the column are omitted as per Fig. 17, the column web will fail as indicated. The loads in these cases being 70,000 lb. for the former and 53,400 lb. for the latter. The load deflection curves for Figs. 16 and 17 are shown by No. 2 and No. 4, respectively, of Fig. 18.

The application of continuity and reduction of connection details for the design of the first arc welded truss-type railroad bridge Fig. 19 resulted in a saving of 33½ per cent by weight in the steel required in the structure. The welded bridge involves 80 tons of steel whereas the riveted design requires 120 tons of steel. In the case of the welded design, the connection details are only about 5 per cent of the weight of the structure, whereas the connection details for the riveted design are about 30 per cent of the weight of the structure.

FIG. 21—CLOSE-UP VIEW OF ADDITION, FIG. 15

**Shows small amount of disturbance in masonry where members are added to an existing structure by arc welding.**

Where corrections in, or additions to, existing structures are to be made, the arc process will show tremendous savings, and as a result, much work of this type, such as the reenforcing of the Great Western Railroad Bridge, at Leavenworth, Kansas, over the Missouri River, has been performed recently. In this case, over

110 tons of plate material, etc., were added to the structure at a figure considerably below the riveting cost.

In the case of the 3-bay welded building, Fig. 20, it was decided to add two bays. To do this, only a relatively small amount of outside masonry was removed to permit of the welding being done as illustrated by Fig. 21.

The major saving in this class of work is in the elimination of drilling holes for rivets and tearing away masonry on the rear side of the members to permit backing up the rivets while being driven.

Due to its many merits, such as lower costs, absence of noise, etc., the arc welding process will undoubtedly come into greater and greater use. The information which is accumulating from its use on relatively simple buildings will make it available in combination with riveting for larger and more complicated structures, and should lead eventually to the possibility of its use almost exclusively on the largest and most complicated structures built of structural steel.

## Discussion

**J. W. Owens:** Mr. Candy brought up two points to which I should like to refer:

The first one is that he partially admitted the advantage, or so-called advantage, claimed for the riveted joint, namely, the possibility of its adjustment by slippage under load as against the non-slippage of the welded joint. This is a point which welding engineers have not conceded.

In the first place, if a structural engineer could produce an integral building or one without a joint, in other words the most perfect building that could be constructed, he would do it. He does not do so because of mechanical and commercial considerations in the manufacture, shipment, fabrication, and erection of the steel. The nearer then that we can approach the ideal of a homogeneous structure, the more perfect will be our buildings, and welded construction approaches this ideal very closely.

Again, a riveted joint is known from tests to slip at 15 to 20 per cent of its ultimate strength, and once a riveted joint starts to slip, you do not know what results such slippage will have on the loads which other parts of the structure will be required to stand and for which such parts were probably not designed. In dealing with naval architects I have found that they have a tendency to stress the so-called advantage of joint slippage because of the complex stresses that the ship's hull is subjected to in service. My point of view is that if welded joints have a working strength greater than the elastic limit of the material welded, the elasticity of the base metal will take care of such stresses. Any stress beyond the elastic limit of the material welded will permanently deform the structure regardless of whether it is welded or riveted. Practically, then, the most perfect structure that can be made is one in which all the joints are welded. However, it should be designed specifically for welding.

The second point I should like to call attention to is Mr. Candy's remarks about the slotted joint. This joint was, I think, first introduced in airplane construction and is today used extensively in this class of work, the tubing being slotted for an insert plate as shown in the accompanying Fig. 1 at A. The Newport News Shipyard has recently extensively employed the slotted joint in the construction of the hull structure of the S. S. *Virginia*. This ship is a sister ship of the *California*, and the largest merchant ship to be built in the United States to date. In this case, the tops and bottoms of her tubular pillars, some of which were 22 in. in diameter and of ¾ in. material, were slotted for plates as shown in C, thus making possible a joint which was twice as strong as the original riveted joint obtained by means of a forged angle-ring riveted to the pillar. This welded connection was made at about one-fourth of the cost of the riveted one. Two of the other applications to which I have applied this joint are shown in B and D. This type of joint will be found very useful in the development of various structural designs. This was called to the attention of the American Welding Society at its fall meeting in Detroit.

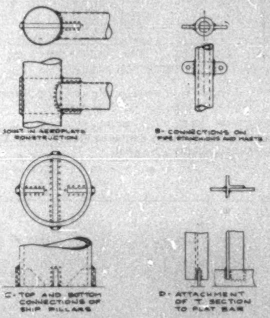
A- JOINT IN AEROPLANE CONSTRUCTION
B- CONNECTIONS ON PIPE STANCHIONS AND MASTS
C- TOP AND BOTTOM CONNECTIONS OF SHIP PILLARS
D- ATTACHMENT OF T SECTION TO FLAT BAR

Fig. 1—Various Applications of the Slotted Joint

I should like to emphasize that, in all my experience with practically every type of welded structure, I have rarely come across a case in which the structure would not be cheaper if welded instead of riveted, provided it had been specifically designed for welding. In my opinion, the time is not far distant (perhaps it will be within the next seven or ten years) when we shall have completely welded ships. The Newport News Shipyard is now welding the major portion of non-strength parts of ships constructed at this yard and a number of the important strength members, *e. g.*, pillars, rudders, frames, etc. Before long, it is expected, we shall be completely welding bulkheads.

**A. M. Candy:** Referring to Mr. Owen's remarks relative to flexibility in structural steel connections, I wish to make the following comments. In riveted designs for beam-to-column connections as the beam is loaded it will be deflected to a certain point, depending upon the loading on the beam, which results in a certain amount of bending in the connection angles which secure the beam end to the column. The very act of bending of the connecting angles relieves the stresses which would otherwise be imposed on the connecting material. In designing steel structures for welding the amount of weld metal which may secure the beam to the column in so far as handling the shear load on the connection, may be entirely inadequate to take care of the stresses which may result at the connection if this amount of metal is placed where it will restrain the end of the beam from separating from the column by the amount which it would have separated had a standard riveted connection been employed. If, for example, the top and bottom flanges of a given beam are to be welded to a column the amount of welding used must be sufficient to carry all of the stresses which will be thrown into the connection point when the beam is loaded, said stresses to be calculated upon the basis that the beam end is fixed to the column and cannot move with the deflection of the beam under load. These secondary stresses which are produced through the connection due to the fixation of one member to the other may in some cases be several times the normal loading which would result on a standard riveted connection. I believe that if Mr. Owens gives this point some little thought, he will readily see the idea which the speaker had in mind when briefly mentioning this very characteristic.

Relative to the slotted construction used in airplane-fuselage manufacture, I believe that Mr. Owens will find that the gusset plates used at the connection points are not slotted but that the tubular members are slotted so that they will slip on over the gusset plates, which are solid, welding being performed around the edges of the tubes where they come in contact with the gusset plates. As a matter of fact, slotting the gusset plates in this type of joint would defeat the very purpose which it is desired to accomplish, namely, to have a solid continuous web member throughout the tubing sections, which are joined by the gusset plate.

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# Welding and Manufacturing of Large Electrical Apparatus

BY A. P. WOOD[1]

Associate, A. I. E. E.

***Synopsis.**—The object of this paper is to show how extensively electric welding is being used in the fabrication of large electrical apparatus. It outlines the use and advantages of welding for supplanting the casting and machinery of parts and describes briefly the welding equipment developed for this purpose and some of the electrical machines produced by this method.*

THE steps required in producing an electrical machine of iron or steel castings consist chiefly of engineering, drafting, making patterns and castings, machining, assembling, and finally, filling and painting.

The tendency of the present day, however, is to produce machines, particularly the larger electrical machinery, of welded steel plates. It is possible now by following the new modern process of fabricating a machine practically to eliminate the pattern shop as well as the foundry.

Welding passed beyond the experimental stage several years ago. Previously, it was principally used for repair work. Automatic welding equipment has recently been developed, which guarantees a much better weld, thus greatly reducing the possibility of personal error present in hand welding and insuring uniformity throughout the length of the weld. Considerable time and money is saved by resorting to automatic welding wherever possible, as it is more rapid than hand welding and there is no loss of welding wire as in the case in hand welding.

A drafting department can quickly produce simplified drawings calling for steel plates to be cut by flame, some of which are easily rolled circular, and then mostly automatically welded together, thus producing a stator or rotor.

By making these large structures of fabricated plates, no expensive patterns are required. Valuable pattern storage space, which had to be increased as time went by is thereby released and can be used for other manufacturing purposes. Foundry space is reduced and the substitution of welded forms for castings results in a great saving of time and eliminates the possibility of a defective casting due to cores shifting, blow holes, cold shots, and pouring gates, which require time to burn and machine off.

The work of the machine shop is reduced to a minimum, as the plates arc-welded together have approximately the finished dimensions, while in a casting there is of necessity a great amount of excess metal which is never twice alike and which requires excessive machining.

The first use of welding in a-c. machine construction was spot welding the armature-core air-duct spacers to the laminations instead of riveting them on. The next development was the adoption about 11 years ago of welded clamping flanges for holding the stator laminations. These flanges consist of sheared-off steel fingers arc-welded to steel retaining plates. About this time, arc-welded air deflectors made of sheet iron and angle iron were introduced.

In 1924, the General Electric Co. designed and built a 1400-kv-a. machine having the stator frame of welded steel plates. This stator consisted of two side plates having the supporting feet as part of the plate. The outside wrapper plate, foot plates, and ribs for retaining stator punchings, were then hand-welded in place. It was lighter than a similar cast machine, and deflec-

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tion tests proved it to be much stronger. The chance of breakage due to handling while in the course of manufacture, or to short circuits after being installed, was greatly reduced. During the three intervening years, practically all stator frames of our machines have been changed over to this new form of construction.

When the steel plate frame is ready for painting it is of nice appearance, as any scale attached to the plates has been removed by sand blasting. No filler being required, the surface is quickly finished with a paint gun.

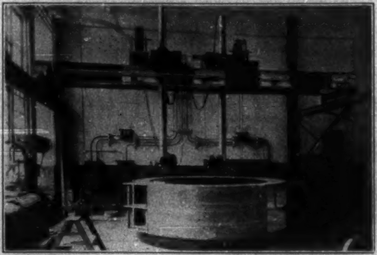

Fig. 1—Stator-Frame Automatic Welder for Frames up to 14 Ft. Diameter

These years of experience have justified the making of arc welded steel-plate machines as large as 40 ft. in diameter for slow speed, and as high as 10 ft. for high speed, and up to the present writing, of capacity up to 100,000 kv-a.

Fig. 2—Stator-Frame Automatic Welder for Frames Exceeding 14 Ft. Diameter

Very extensive tests have been made on samples of plates welded together with single-, double-, and triple-layer welding—both hand and automatic—so that there is no question about the sort of welding to use for any particular design.

Wherever possible, on vertical or horizontal stators, rotors, bearing brackets, etc., hand welding has been superseded by automatic welding. On large diameter stators two or more circular plates made of segments, when in the same plane, are welded together by a semi-automatic hydrogen-enveloped arc. This results in a ductile weld that is easy to machine or grind and will not break if accidently stressed by being dropped in handling.

For general work, three principal types of automatic welding machines have been developed. On the first type of welding machine, the welding heads are stationary and the piece to be welded is rotated past the heads. It is, however, only practical to rotate the work up to a certain diameter (see Fig. 1). With the second type of automatic welding, used for larger diameters, the radial arms of the automatic welding machine are made to rotate by a motor drive, Fig. 2. The third type of automatic welding is a straight-line welder in which the work is stationary and the welding head is moved.

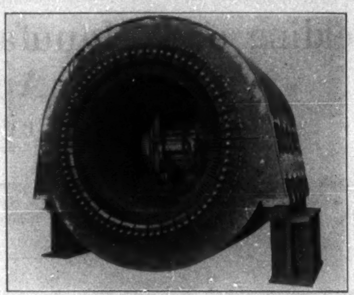

Fig. 3—Stator with Punchings for 50,000-Kv-a. Synchronous Condenser

The large automatic welding machines shown in Figs. 1 and 2 weld from 6 to 8 ft. per minute. The current used is between 300 and 400 amperes at 20 to 30 volts, depending on the gap between the pieces to be welded. Direct current is used.

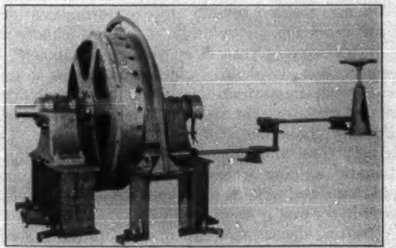

Fig. 4—A Welded Rotating Stator Frame for Super-synchronous Motor

The semi-automatic hydrogen-enveloped welding uses approximately 250 amperes at 40 to 60 volts, as it requires a higher voltage to maintain the arc.

The welding rod, or reel, on the automatic machines is of G. E. Type-B shielded wire, which consists of a steel core and outer steel layer between which is the flux. A high speed of welding is possible with this wire.

A large horizontal stator of 50,000 kv-a. is shown, Fig. 3. You will note the supporting feet are cut out as part of the side plates and welded to a heavy plate which is drilled for the holding down and adjusting bolts. The stator is split horizontally to aid in shipping, the two halves being held together by bolts and dowels inserted in the rectangular blocks, which were completed as a unit before welding in the stator. As a result of arc welding, we have produced large stator frames in 90 deg., 120 deg. and 180 deg., sections that require no setting up on expensive iron floors for machining or dowelling at the splits, as this operation is entirely eliminated. The ventilating air openings are located in the circular outer apron, or wrapper sheet, and are covered with punched metal covers. The laminations are mounted on the welded ribs and clamped tightly together by welded non-magnetic steel clamping flanges.

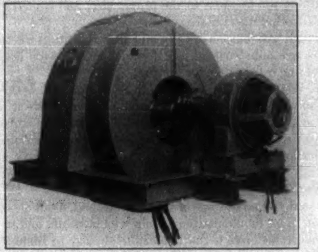

Fig. 5—Welded Beam Base for 2500-Kv-a. Synchronous Condenser

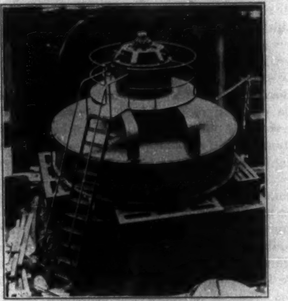

Fig. 6—Vertical Water-wheel Driven Generator Practically Entirely Welded

A rotating stator frame for a G. E. super-synchronous motor built up of arc welded rolled plates is shown in Fig. 4.

The next step in the elimination of castings on the horizontal machine was to replace the cast iron base with one of welded beams. (See Fig. 5.) This design has been developed and built for machines up to 50,000 kv-a.

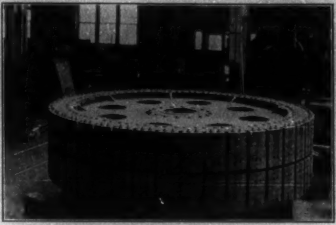

Fig. 7—Welded Rotor Spider for 19,700-Kv-a., Rev. per Min. Generator

Fig. 6 shows a medium sized vertical alternator, the mechanical parts of which are almost entirely of welded construction. The stator frame is similar in construction to the horizontal stator previously described, except that the bottom plate is of larger diameter, to permit of fastening to the foundation plates. A heavy rolled ring is welded to the top of the outside wrapper plate for supporting the top bearing bracket.

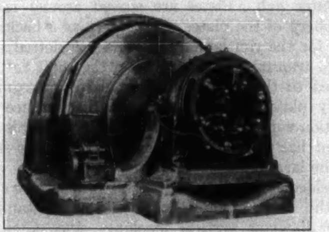

Fig. 8—Welded Air Deflector

A structural steel welded upper bearing bracket consisting of two rolled I-beam girders between which is bolted a welded housing carries the upper guide bearing and supports the thrust bearing which carries the weight of the rotor, waterwheel runner, and thrust. The ends of these girders are cut off to a rather large radius and a steel plate is rolled to this radius and welded to the web of the beam. This construction does not appreciably affect the strength of the beam and gives the structure a more pleasing appearance. The platform around the exciter is made of plates, welded together, and the exciter, itself, has a frame made of a steel slab rolled to shape. Where the load on the upper bearing bracket is so large that rolled steel beams of sufficient size cannot be obtained, these brackets are made up by plates welded together. We have recently finished two such fabricated beams similar in section to the rolled I-beam which are 30½ ft. long and 6 ft. high. The flanges and webs are welded together throughout their entire length. Between these beams is carried a welded thrust bearing housing designed to support a load of 350 tons.

A large number of cast rotor spiders has been replaced by various designs of welded plate construction. On the smaller spiders the hub is cut from thick steel plate or made from casting stock, to which is welded a center web-cut out of heavy rolled plate. The rotor rim is steel plate rolled to the proper diameter and welded to the center web. This outside rim may be either a single plate with a butt welded joint or made of two rolled plates having the joints staggered and welded together completely around the outer edges. Since the rim plate is welded to both sides of the web plate around the complete periphery, the welded joint of the rim does not have to take the entire load of the centrifugal force of the poles.

For the larger class of rotors a welded-plate spider is used to support a rim built up of thin laminations. Such a design for a 19,700-kv-a. generator is shown in Fig. 7. The center spider consists of circular plates for the top and bottom members which are welded to a center hub. Plates are spaced around the outer periphery of the plates which serve as a backing support for the rim laminations and are slotted for keys which transmit the torque from the shaft to the rim. Bolted to the bottom circular plate are segments of heavy plate which act as a braking surface and in addition support the weight of the rim. This type of design has been quite generally adopted as standard for the larger slow-speed vertical generators.

Welded structural-steel bearing brackets for supporting the lower guide bearing have been standard on large diameter vertical machines since about 1922. Ordinarily, these brackets are built of rolled shapes fabricated by flame cutting and welding. Mounted on the lower bracket are combined brakes and jacks which are also fabricated of parts welded together.

The original cast iron enclosing shields for positive ventilation on horizontal machines have been replaced by a combination welded and riveted sheet iron shield. Fig. 8. clearly shows the method of obtaining a large radius to the shields which is pleasing to the eye and seems so necessary when castings were used. An open-type spot-welded shield has been standard for a good many years.

The development of the art of welding and flame cutting has marked a new era in the design of electrical machines, particularly those which are either very large or special. The advantages of obtaining a structure which is homogeneous, free from possible casting defects, long and costly machining, and which lends itself so admirably to changes in design without any more expense than the change of a drawing, are, in the writer's opinion, so great that they cannot be ignored.

## Discussion

**F. D. Newbury:** I wish to endorse and, if I can, emphasize what Mr. Wood has just said about the fundamental importance of this change in our machinery construction.

The introduction of welding and the use of rolled sections, instead of castings, has given the designer an entirely new basis for his design. Instead of the foundry and the pattern shop we have substituted the steel rolling mill, the gas torch, and welding equipment. As one man has recently expressed it, a fabricating shop for electrical machinery now is something like a carpenter's shop: it contains a stock of standard shapes, something to cut them to the proper size, and something to nail them together into the shape desired.

I would also emphasize the fact that to obtain the advantage of this new construction, the designer must design his structure for welding rather than for casting.

Mr. Wood also pointed out, I believe, that unless the designer does so take advantage of the new method, there is apt to be little saving in cost in the structural parts over corresponding cast parts. The great saving, and the obvious saving, is in the elimination of patterns. So this new method is applicable generally to special designs for larger machines that are seldom duplicated.

To take full advantage of this new method, machine operations as such must be eliminated as much as possible, and in our own experience we have found it possible already to build frames for machines of very large size with no machining operations except drilling the holes for certain through-bolts.

But, while there are obvious advantages from a cost and delivery standpoint in the elimination of patterns and in the elimination of castings, this very fact has introduced rather serious problems for the factory administrator. It is not an easy thing for the factory manager to become reconciled to the fact that he is losing his foundry load, and it is a real problem for the manager to face, to scrap millions of dollars of factory equipment due to the introduction of a new method. But American managers have always boasted of their willingness to scrap obsolete equipment and they are now faced with the fact that a great deal of the foundry equipment of the electrical manufacturers and undoubtedly other manufacturers, as they take up this new work, must be scrapped in favor of a newer and less expensive method of construction.

We have also found an incidental advantage in the changed attitude of mind of our foundry friends. Since they have experienced this new competition there has been less thought about tonnage and more attention has been given to methods of reducing foundry costs, as for example, through use of thinner sections.

Of course, this new method will not completely eliminate castings by any means. The casting method will show lower costs, for parts of smaller diameters, and for parts that require considerable fabrication work, and particularly where the size and volume of the output warrant machine-foundry methods.

There is just one more point I should like to call to your attention, that the advantages of structural materials in our electrical machinery have been recognized for many years. Some 28 years ago the 5000-kw. engine-type generators that were built for the Interborough elevated and subway plants in New York City had a completely fabricated rotating part, with riveted built-up spiders. About 18 years ago we attempted to design a line of d-c. machines with entirely structural parts, but that plan was abandoned because there was no satisfactory low-cost method of assembling available at that time.

About 15 years ago I was interested in a structural frame design that we gave up because of cost. There riveting was contemplated instead of welding.

So it should be placed to the credit of the welding process that we are now able to make these savings and achieve these very desirable results in electrical machinery design.

**B. L. Barns:** A very important advantage of welded construction is the greater freedom of the designer in using dimensions and proportions best suited for the electrical characteristics that are desired. When large and expensive patterns were used the electrical designs were often compromises. When a particular rating was required the proportions of the machine were often largely determined by existing patterns with the result that the active material was not always used to the best advantage or some characteristic was not as good as it might have been. With this new construction the designer has greater freedom in choosing the proportions of the active material and as a result better machines are being built.

Another advantage that has been experienced in the factory with which I am connected is a material reduction in delays in manufacture due to defective castings. Even though great care may be exercised in the inspection of castings in the foundry, occasionally defects or flaws are discovered after the machine work is partly done. If the defect is of a sufficiently serious nature it is necessary to scrap the casting and order a new one. This, of course, upsets the whole schedule of production and a delay in shipment probably results. On the other hand the welded construction is free from hidden defects and manufacturing delays are correspondingly reduced. The absence of delays from these causes is an economy that is incidental to this type of construction.

**H. M. Hobart:** In spite of all the nice things said about these machines, I think the designs they have been turning out recently are quite unbeautiful. I wonder if they can't, without abandoning all these advantages, bring in a little less unloveliness.

**F. D. Newbury:** We have often had this point about appearance of the machines brought up. My answer has always been that a thing is good-looking if it is designed according to correct mechanical principles, if there is no imitation about it. A straightforward design is always good-looking to an engineer.

**B. L. Barns:** Our company just recently received an order for several large low-speed machines. The standard which was set on the floor was flat, like a pancake, and had a large diameter. My assistant, Mr. Sills, got the happy idea of building the frame with flat sides, a polygon. The purpose of that was to add vertical lines to the frame and make it look higher. The upper bearing bracket for supporting the thrust-bearing, we intend to build of the girder type, two girders side by side with the thrust bearing support in between. So we carried out the same idea and made all the lines on the girder straight. We built a small model which I took to the customer's office and exhibited, and the enthusiasm for the general appearance was unbounded. They didn't want a round machine after that.

**A. P. Wood:** I might answer Mr. Hobart by saying that the new generation of designers has probably been influenced by modern cubist tendencies in art.

In order to help beautify the welded steel construction you will note by photographs in the paper that the effect of rounded corners is obtained by flanging the thinner sheet-metal enclosing hoods. In some cases a curve as large as 6 in. is used which eliminates the square appearance. But from a manufacturing point of view, the heavy plates which are passed through large rolls, cold, must remain squared, as in this shape they best lend themselves to automatic welding.

I believe that, as many others have, the more you see of machines of this construction the better you will like them.

# Spectroscopic Prediction

BY ROBERT A. MILLIKAN[1]
Member, A. I. E. E.

NEVER in the history of science has a subject sprung so suddenly from a state of complete obscurity and unintelligibility to a condition of full illumination and predictability as has the field of spectroscopy since the year 1913.

It is my privilege today to recount the rapidly following steps in this spectacular advance which the Germans call *die Fortschritte der Spectroscopie*,—a peculiarly appropriate phrase since it is so beautifully descriptive of the step-by-step process by which theory and experiment interplay in rapidly bearing forward the body of our ever advancing knowledge.

## I. The Bohr Theory

The great step which ushered in the new era was partly theoretical, partly experimental. It was taken when in 1913 Bohr[2] first thought of applying to the interpretation of spectra the then rapidly advancing idea that the frequency of a light-ray might be taken as a measure of the energy lost by its emitter or gained by its absorber—an idea first suggested by Planck[3] in 1900; much more sharply formulated by Einstein, though still without adequate experimental warrant, in 1905[4]; definitely and quantitatively proved for photoelectric effects by a long series of experiments culminating in 1915[5]; and now the firm basis of the whole of modern spectroscopy. It is the most powerful instrument in spectroscopic prediction, and yet an idea which is completely at variance with all nineteenth century modes of thought, and thus far wholly irreconcilable with all the phenomena of interference which still find their interpretation only in terms of such a spreading-wave theory as denies any relation between frequency and energy. This relationship must be regarded simply as a new experimental fact holding in the domain of electronic phenomena, and of as yet unknown relationship to the large scale phenomena for the interpretation of which nineteenth century theories were developed.

And yet this great step of Bohr's, bold as it was, is after all a beautiful illustration of the conservative, step-by-step method by which physics has made most of its great advances. Instead of breaking away entirely from the past, as the foregoing comments may have indicated that he did, Bohr actually built conspicuously upon it. He incorporated the whole of celestial mechanics into the structure of his new atomic mechanics, merely adding to the old the features demanded by the newly discovered facts of radiation. Since the positive nucleus of the hydrogen atom attracts the negative electron in accordance with a law analogous to that which holds the earth to the sun, there was obviously no procedure consistent with the principle of minimum hypothesis, always followed by science, save to call upon the centrifugal forces engendered by orbital motion to prevent the attracting bodies, whether celestial or electronic, from rushing together under the influence of their mutual attractions.

But these hypothetical electronic orbits confront a condition not met with at all in the case of the equally hypothetical celestial orbits; for a planet or other celestial body has no mechanism for losing any appreciable fraction of its energy in a humanly speaking finite time, while in glowing hydrogen the atoms are continually interchanging considerable fractions of their energy with ether waves, sometimes absorbing and sometimes emitting such waves. The new experimentally discovered law of this interchange, *viz.*, $E_1 - E_2 = h\gamma$, in which the two $E$'s represent energy before and after emission, and $\gamma$ the emitted frequency, $h$ being constant, simply had to be added to the laws of celestial mechanics to obtain the laws of atomic mechanics.

This addition of the old theory and the new experimental facts constituted the essence of the Bohr theory. It was the old theory, *i. e.*, the laws of celestial mechanics, that required that when a hydrogen atom emitted radiation in accordance with the equation $E_1 - E_2 = h\gamma$, the electron drop into a new orbit of smaller radius, for in celestial mechanics the size of the orbit is fixed by the energy of the orbital system. The possible radii of the orbits of the electron of the hydrogen atom were thus limited to those whose energies differed by the observed emitted frequencies multiplied by the universal constant $h$, the dimensions of which were those of *moment of momentum*, and the observed emitted frequencies in hydrogen were such as to require that the possible orbits be limited to those for which the moment of momentum of the electron in its orbit progressed by unit steps, each an integral multiple of $h$, or, more accurately, of $\frac{h}{2\pi}$.

Bohr thus put into his original picture three elements, the first theoretical, the last two experimental: 1, the laws of celestial mechanics, 2, the newly observed relation between frequency and energy, 3, the observed series of frequencies in the hydrogen spectrum. His boldness lay in two points; first, in that he postulated

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[1] Director, Norman Bridge Laboratory of Physics, Univ. of California, Pasadena, Calif.

[2] Niels Bohr, *Phil. Mag.*, *26*, 1, 1913; *26*, 476, 1913; *26*, 857, 1913.

[3] Max Planck, "Warmestrahlung," 1st Ed., 1900.

[4] Einstein, *Ann. d. Physik*, *17*, 132, 1905; *20*, 199, 1906.

[5] Millikan, *Phys. Rev.*, *7*, 362, 1916.

*Third Steinmetz Lecture, delivered before the Schenectady Section on April 20, 1927.*

*non-radiating* electronic orbits and thus denied the universal validity of Maxwell's equations; second, in that he ignored entirely, and purposely, the consideration of a *mechanism* of radiation. How an electron in jumping from one orbit to another of different energy can emit a radiation of frequency proportional to the energy-difference no one has as yet been able to suggest. Bohr simply set down and used the newly discovered experimental fact and forgot all about mechanism, a procedure which fifty years earlier had been so effectively used and so abundantly justified in the establishment and utilization of the second law of thermodynamics.

The original, simple theory of Bohr quickly had quite as remarkable quantitative successes as had had two hundred years earlier the corresponding orbital theory in celestial mechanics of Copernicus-Galileo-Newton. The latter not only furnished a satisfactory interpretation of the retrograde motions of the planets which it was devised to explain, but it made possible the prediction of the precise instant of eclipses, predictions which observations can now check with extraordinary precision, and therein lies its chief claim to modern acceptance.

Similarly, the Bohr theory not only furnished the first satisfactory interpretation of the hydrogen spectrum which gave it birth, but because of its orbital assumptions it enabled the Rydberg spectroscopic constant to be predicted from the accurately known values of the charge of the electron, its mass, and the value of $h$. *Purely spectroscopic observations check this computed value to within one-fourth of one per cent*, and therein lay the first brilliant success of Bohr's orbital assumptions, though by no means their only one.

The second and even more unambiguous success of Bohr's assumptions came three years later and constitutes what I shall call the second forward step in the process of spectroscopic illumination and prediction. It was an experimental step taken when Paschen made his very accurate measurement of the very slight difference in position, or wave length, of corresponding hydrogen and helium lines. This difference came out precisely as predicted from the four-fold difference in the masses of the central bodies about which the same sort of a body, a single negative electron, was supposed to be rotating in each case.

This altogether extraordinary and accurately quantitative check between prediction and experiment, constitutes perhaps as striking credentials for an orbital conception as has ever been met with anywhere in the history of orbital ideas, celestial or electronic. It seems quite uninterpretable save in terms of the conception of two widely different masses both of dimensions minute in comparison with their distance apart, revolving, just as the sun and the earth on the one hand, the nucleus and its electron on the other, are supposed to do about their common center of gravity.

## II. RELATIVISTIC INTERPRETATION OF FINE STRUCTURE

The next important step in the advance of modern spectroscopy was taken when in 1916 Sommerfeld applied Einstein's relativistic considerations to the interpretation of the so-called fine structure of spectral lines, and in so doing brought still further powerful support to the theory of electronic orbits.

Bohr's simple theory had considered only circular orbits, the radius $r$ of a given orbit remaining constant and the azimuth $\varphi$ alone varying as the electron moved about in its orbit. In its inmost orbit the electron of the hydrogen atom had one unit of moment of momentum, the unit being actually $\frac{h}{2\pi}$, in its second orbit two units, in its third three, etc. This condition could be as well fulfilled with certain types of elliptical orbits as with circular orbits, but in that case two independent variables $\varphi$ and $r$ would have to be introduced to describe the motion in each ellipse. Sommerfeld applied the same sort of quantum conditions to both of these variables as Bohr had applied to $\varphi$ alone before. He made the total moment of momentum[6] of the system—the so-called total quantum number—the sum of an azimuthal and a radial quantum number, the way in which the total moment of momentum was divided between the two determining the ellipticity of the orbit. Thus, when the total quantum number was 1, the azimuthal quantum number had to be 1 and the radial quantum number 0, or else the azimuthal 0 and the radial 1. The first condition meant physically a circular orbit as in the simple Bohr theory, while the last meant a radial oscillation in which the electron had to pass through the nucleus, a physical impossibility. Hence the inmost orbit designated as a $1_1$ orbit (the first integer denoting total, the last azimuthal quantum number, the radial being the difference between the two) had always to be a circle. For total quantum number 2, however, two different orbits were possible, namely, a $2_2$ orbit, a circle (later designated a $p$ orbit), or a $2_1$ orbit, an ellipse (later called an $s$ orbit) having its major axis equal to the diameter of the circle and twice its minor axis. The orbits of total quantum number 3 might have the shapes $3_3$, $3_2$, or $3_1$, as shown in Fig. 1, namely, a circle and two ellipses all having the same major axis but minor axes in the ratios 3, 2, 1.

So long as the Newtonian law of attraction governed the motions, all the orbits of a given total quantum number would have exactly the same energy (for this would be determined solely by the length of the major axis of the ellipse) and hence be spectroscopically indistinguishable since the only directly observable quantity in spectroscopy is the emitted frequency determined by the electron jump from one orbit to another, *i. e.*, by the difference in the *energies* of two orbits. But when the Einstein relativity corrections are applied to the Newtonian laws there is introduced a change of mass with speed which makes the energy of binding of the electron to the nucleus in the case of a series of orbits of the same major axis (total quantum number) slightly greater the greater the ellipticity of the orbit, and hence makes the electron jumps into these orbits from a given position correspond to a number of slightly different frequencies, thus introducing fine structure into spectral lines. The theoretical procedure here adopted is in part the same as that used by Einstein in explaining the precession in the perihelion of mercury, *i. e.*, it is another instance of the application of the laws of celestial mechanics to the domain of atomic mechanics. The quantitative prediction of mercury's precession, however, involves the general relativity theory, whereas the foregoing has to do only with "special relativity."

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[6] More correctly "quantity of action" defined by $\int P_\phi \, d\,\phi + \int P_r \, d\,r$

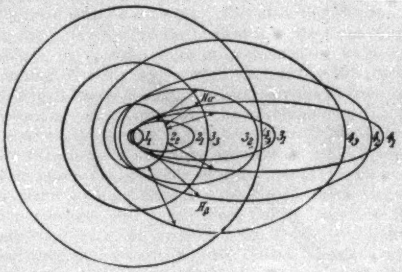

FIG. 1

This Sommerfeld relativistic interpretation of fine structure introduced new possibilities of spectroscopic prediction which from 1919 to 1924 had extraordinary successes. Thus, all the lines of the so-called Balmer series of hydrogen which consist of jumps into the state of total quantum number 2, a state possessing only two possible orbits, one a circle and one an ellipse, should reveal a fine structure corresponding to the difference in the energies of these particular circular and elliptical electronic orbits. To a first approximation they should actually all be doublet-lines with an accurately predictable difference in wave-length, or in frequency separation; and again *the prediction could be made wholly from the laws of orbital mechanics.* The theoretical value of the frequency separation of the hypothetical hydrogen doublets came out 0.365 cm.$^{-1}$ frequency units. Now, with instruments of high resolving power, not only are these hydrogen lines *all* found actually to be doublets just as predicted, but the most accurate determination of this separation, obtained from $H\,\beta$, recently made by Dr. William V. Houston in the Norman Bridge Laboratory, comes out 0.36 cm.$^{-1}$—a value within a per cent of the computed value, an altogether outstanding and spectacular demonstration of the power of the physicist's newly discovered methods of spectroscopic prediction.

Again, the theoretical relativity formula made the frequency separation of a corresponding pair of lines vary with the fourth power of the atomic number so that the corresponding lines in ionized helium—like atomic hydrogen a simple nucleus-electron system but with a charge on the nucleus twice that in hydrogen—should be sixteen times as far separated as in hydrogen. This prediction also was accurately verified as early as 1916 by Paschen,[7] his observed spectrum divided by 16 yielding, with extraordinary accuracy, 0.365 ± 0.0005—another quantitative triumph of orbital theory.

Equally significant and even more beautiful as a piece of powerful analysis and wonderful prediction was Epstein's[8] work on the effect of a superimposed electrical field in modifying electronic orbits of the foregoing sort, for he thus predicted correctly practically all the intricacies of the Stark effect—a triumph not only of the orbital theory but of the theoretical analysis itself.

But perhaps the most spectacular success of the relativity formula as applied to the interpretation of spectroscopic fine structure came when this formula predicted with approximate correctness the frequency separation of the so-called $L$ doublets in the X-ray spectra of the heavy elements like uranium. Being a doublet corresponding, like the hydrogen doublets, to the electronic orbits of total quantum number 2, this ought (if it was actually a relativity doublet as assumed by Sommerfeld), to have a frequency separation obtainable by multiplying the observed separation in the case of hydrogen by the huge factor of 71 million, for this represents the fourth power of the ratio of the atomic number of uranium 92, to that of hydrogen 1. This prediction also checked with experiment.[9]

*No theoretical formula in the history of physics has had more spectacular successes than Sommerfeld's relativity formula as applied to spectroscopic fine structure.*

## III. REGULAR AND IRREGULAR DOUBLET LAWS IN OPTICS

Another step that introduced new power into spectroscopic prediction was taken about 1920 in the development of high-vacuum "hot-spark" spectrometry[10], for this enabled Dr. Bowen, Dr. Sawyer, and me not only to explore new regions of the ultraviolet spectrum and to add largely to our knowledge of spectra particularly in the case of the light elements, but also to develop new methods for the identification of lines and to discover new relationships that soon forced new interpretations and assisted in the introduction of fundamentally new conceptions into physics. Few more interesting instances of the exact verification of spectroscopic predictions can be found than are recorded in the work on stripped atoms.[11] Indeed, the discovery that our high potential vacuum sparks produced such atoms was made by predicting with the aid of the Bohr theory the exact positions and character of the lines to be expected from atoms stripped of all their valence electrons and hence reduced practically to hydrogen-like systems. It was only such reduction that at first made the predictions possible. The predicted lines were all found in the case of all the atoms of the first two rows of the periodic table except fluorine, which holds its electrons too tightly to enable our sparks to strip them all off. There were thus obtained for the first time in the field of optics the spectra of a long series of atoms of precisely like electronic structure but varying nuclear charge, namely, the series consisting of stripped Li, Be, B, C, N, O, and the second series consisting of stripped Na, Mg, Al, Si, P, S, Cl.

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[7] Paschen, Bohr's Heliumlinien, *Ann. der Physik*, *50*, 901, 1916.

[8] P. Epstein, Zur Theorie des Stark Effekt, *Ann. der Physik*, *50*, 489, 1916.

[9] See Sommerfeld's "Atombau und Spectrallinien," 4th Ger. ed., p. 445.

[10] Millikan, *Proc. Nat. Acad. Sci.*, *7*, 289, 1921.

By the study of these series it was found that two laws found earlier in the field of X-rays and called the regular and irregular doublet laws held also in the field of optics, and they have since constituted powerful instruments for the prediction and identification of spectra. We have found them to be applicable to all series of like electronic structures, whether stripped or only partially stripped. The irregular doublet law enables one, if he can only get started on such a series, to predict the precise place in the spectrum, *i. e.*, the precise wave-length at which the corresponding lines of the other elements in the series are to be looked for, while the regular doublet law tells him the precise character of the line he should seek, *i. e.*, the frequency separations to be expected in its fine-structure. The foregoing is, then, a step in which the experimental foot goes forward. Next comes again the theoretical step.

## IV. INNER QUANTUM NUMBER

The only cause of spectroscopic fine structure thus far considered has been the relativity cause which operates by virtue of a difference in the shapes of orbits of the same total quantum number. But it was found as early as 1920[12] that that was not enough to account for all the facts of fine structure. In X-rays, for example, the so-called $L$ orbits or $L$ levels correspond to a total quantum number 2, and this permits of only two different orbits, one a circle designated as a $2_2$ orbit, and one an ellipse designated as a $2_1$ orbit; but X-ray absorption experiments brought to light three different levels or orbits, all close together in frequency, in which $L$ electrons were actually found. Two of these followed the relativity law, also known as "the *regular* doublet" law referred to in the last paragraph. The frequency difference of these two levels varied with the fourth power of the atomic number, as demanded by the relativity equation. These two levels are represented by the two diverging lines marked $L_{II}$ $L_{III}$ in Fig. 2. The third level, $L_I$, is seen to follow an entirely different law for it runs everywhere parallel to $L_{II}$. The frequency difference between $L_I$ and $L_{II}$ follows what was called *the irregular doublet* law in the last paragraph, so that the geometrical representation in Fig. 2 of the irregular doublet law is parallel lines, of the regular doublet law diverging lines. Similarly, in the field of optics there are found *experimentally* three levels, or orbits, corresponding to the total quantum number 2, instead of merely the two permitted by the relativity theory. Since, then, only two different shapes were possible, Bohr and Sommerfeld introduced the idea that two orbits of the same shape, but of different orientations might exist, and that some dissymmetry in the central force-field gave these two orbits slightly different energies. They introduced a so-called inner quantum number generally denoted by the symbol $J$ to take care of this variation in orientation, just as changes in azimuthal quantum number took care of variations in shape.

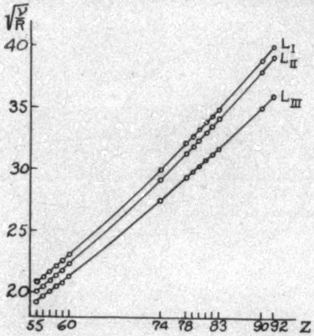

FIG. 2

The difference in the frequencies of the familiar doublet lines in lithium, for example, was supposed to be due to the fact that these two lines represented jumps into a common orbit called an $s$ orbit from two orbits which differed only in inner quantum number, *i. e.*, orbits of different orientations but the same shapes,—in this case circles, or 2, 2 orbits, known as the $p_1$ $p_2$ orbits. The *s* orbit, on the other hand, into which these two electrons jumped to form the lithium doublet, was the third possible orbit of the total quantum state 2, namely, the $2_1$ orbit of elliptical shape, the major axis being twice the minor. The two circular or *p* orbits differed only slightly in frequency or energy, but the change in energy in going from either of the *p* orbits to the *s* orbit was relatively very large, enormously larger than could be accounted for by the relativity effect introduced by change in shape alone. One of Bohr's most penetrating and important contributions to modern spectroscopy was made when in 1922[13] he found a very simple orbital interpretation of this large difference in energy. Thus the elliptical, or $2_1$, orbit in hydrogen and helium differs only slightly in energy from the circular $2_2$ orbit because, with a simple nucleus-electron system, there is nothing but the relativity cause to make a difference in energy, but in lithium, with its two close-in electrons in the *K* shell, and its one *L* electron in a much larger orbit of either circular form ($2_2$) or elliptical form ($2_1$) the case is quite different. For when this electron is in the $2_1$ orbit, since the nucleus is at the focus of the ellipse, the electron must, at perihelion, dip inside the circular *K* orbits of the two *K* electrons, as it is shown in Fig. 1 to be doing, and there be relieved from the screening effect of these two electrons for it. In other words because of this *penetration of the elliptical orbit inside the K shell* the electron when in the $2_1$ orbit gets into a field of force several times as intense as it would if it did not penetrate the *K* shell. It is thus, on the average, very much more tightly bound to the nucleus than is the electron in the $2_2$ orbit which does not thus dip inside the *K* shell. Hence, wherever there is such an inner shell to penetrate, the energy difference between the $2_1$ and the $2_2$ orbits will be very much larger than the relativity difference. The very beautiful way in which this sort of explanation fits the observed facts whenever there are inner shells to penetrate constitutes another extraordinary triumph for the orbital conception. This Bohr mode of interpretation thus called on differences in *shape* with the consequent differences in interpenetration to account for the difference in energy between the *p* and *s* orbits, and left only differences in *orientation* with the same shapes, to account for the difference in energy between the $p_1$ and the $p_2$ orbits.

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[11] Bowen and Millikan, *Proc. Nat. Acad. Sci.*, *10*, 199, 1924; *11*, 119, 1925; *Phys. Rev.*, *25*, 295 and 591, 1925; *24*, 209, 1924; *28*, 923, 1926.

[12] Sommerfeld, *Ann. der Physik 63*, 221, 1920. See also "Atombau und Spectrallinien," Chap. 8.

## V. The Spinning Electron

Now the extraordinary and disconcerting fact which Dr. Bowen and the author brought sharply to light as soon as we had obtained and hence could compare the spectra of a long series of stripped atoms like Li, Be, Bo, C, N, O, all of which had exactly the same electronic structure but varying nuclear charge, was that *the difference in energy between the two circular $p_1$ $p_2$ orbits varied with atomic number in precisely the way demanded by the relativity equation.*

There had been indications of this relation earlier. Sommerfeld in the first edition of his book, 1919, had suggested it but in later editions had discarded it as untenable because theoretically impossible and not experimentally justified. No unambiguous evidence could in fact be got until we had obtained a long series of atoms of identical electronic structures and varying nuclear charge to compare. We then found to our amazement, by careful quantitative studies, that *the energy difference between the $p_1$ $p_2$ orbits followed in every respect the relativity equation,* though it could not possibly be due to a relativity cause, since this cause required differences in shapes of orbits, while the $p_1$ $p_2$ orbits could not have differences in *shapes* but only differences in orientation.

In papers published in 1924 and 1925[14] we therefore stated it as one of the most interesting problems of theoretical physics to retain relativity as a cause of fine structure in hydrogen and helium, and indeed in general, and yet to find another nonrelativistic cause "magnetic, or magnetic and electrostatic combined" which would follow exactly the relativity equation.

Probably never before in the history of physics had such an extraordinary—so well nigh impossible—a condition been imposed. And yet within a year of our statement of the problem, two young Dutch physicists, Uhlenbeck and Goudsmit[15] stimulated partly by our work, partly by other difficulties with existing theory, pointed out especially by Landé and having to do with the so-called anomalous Zeeman effect, had found in the *assumption of the spinning electron* another cause of fine structure which followed exactly the same law in all respects as the relativity cause. The incident furnishes as striking an illustration as the history of physics thus far affords of the power of experimental and theoretical methods combined for predicting new phenomena, interpreting old ones and thus slowly but inevitably, step by step, forcing open nature's hitherto fast-bolted doors.

The new physical conception introduced by Uhlenbeck and Goudsmit is that every electron within an atom is not merely revolving in an orbit but at the same time rotating, just as does a planet, on its own axis. There are assumed to be but two possible directions of spin, 180 deg. apart, but the moment of momentum of spin is assumed to be always the same, namely, exactly one-half unit of moment of momentum *i. e.*, $\frac{1}{2}\,\frac{h}{2\pi}$. Such a conception introduces precisely the right amount of energy difference between the $p_1$ $p_2$ circular orbits which is necessary to account for their observed spectroscopic frequency separation. This effect is simply superposed upon the relativity effect, thus making the fine structure even in hydrogen and ionized helium somewhat more complex than could be accounted for by the relativity effect alone. *This newly predicted complexity has just been found by new and more refined measurements by Dr. Houston to fit the experimental facts much better than did the old theory.*

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[13] N. Bohr, "Three Lectures on Atomic Physics," Vieweg Braunschweig 1922. Also *Ann. der Physik* *71*, 228, 1923.

[14] Bowen and Millikan, *Phys. Rev.* *24*, 209-228, 1924; *Proc. Nat. Acad. Sci.* *11*, 119, 1925; *Phil. Mag.* *49*, 923, 1925.

[15] Uhlenbeck and Goudsmit, *Nature* *117*, 264, 1926.

## VI. The New Spectroscopic Rules

With the aid of this new conception it has now become possible to make a nearer approach than heretofore to presenting a physical interpretation of a group of remarkable spectroscopic rules developed, largely empirically, within the past two years by Russell[16], Heisenberg,[17] Pauli,[18] and Hund[19] and embracing in an altogether remarkable way most of the facts of spectroscopy known up to the present. The success with which these empirical rules describe the facts of spectroscopy is little less than magical. These rules naturally all start with, and grow out of, the fundamental assumption underlying all quantum theory, namely, that all periodic motions must be quantized, *i. e.*, that periodic motion itself is unitary in its nature. As applied to atomic mechanics this means simply that all moments of momentum characteristic of the periodic motions within the atom are to be assigned characteristic quantum numbers and are to be allowed to change only by unit steps.

In the case of each individual electron there are just four sorts of such moments of momentum to consider. In other words there are four elements necessary to the complete description of an electron's motion within the atom, namely 1, the size of its orbit, 2, the shape of its orbit, 3, the orientation of its orbit in space, and 4, the orientation, or direction, of its spin. 1. The total moment of momentum (quantity of action, see p. 724) of an electronic orbit is characterized by its total quantum number $n$ introduced by Bohr. This fixes the size (or major axis) of the orbit. 2. The azimuthal quantum number which, with a given $n$ or major axis, fixes the shape (minor axis) of the orbit has heretofore been characterized by the quantum number $k$. For some reason not yet fully understood, but doubtless of profound physical significance (see below), in order to make the new spectroscopic rules fit the experimental facts it is found necessary to reduce by unity all values of $k$ heretofore assigned. Since, however, we are not yet ready to discard entirely for the old purposes the old interpretations, this reduced value of $k$ is for convenience denoted by a new symbol $l$, so that merely by definition $l = K - 1$. Thus for an $s$ orbit $l = 0$, for a $p$ orbit $l = 1$, for a $d$ orbit $l = 2$ etc.

3. The projection of the orbital moment of momentum $l$ upon any fixed direction of reference, which, in the consideration of the Zeeman effect, is the direction of the applied external magnetic field, is quantized and designated by the symbol $m_l$. This projection obviously fixes the orientation of the orbit in space. The physical significance of the fact that this projection is quantized is that only certain definite orientations of this orbit are possible (such special quantization is directly proved by the so-called Stern and Gerlach experiments).

4. The projection of the moment of momentum of spin upon the fixed direction of reference is designated by the symbol $m_r$. As stated above, there are supposed to be in each atom but two possible directions of spin, 180 deg. apart; so that $m_r$ of course determines in which of these two directions a given electron is spinning. The quantities $m_l$ and $m_r$ are usually called magnetic quantum numbers merely because of their use in connection with magnetic fields.

Now one of the new and very illuminating spectroscopic rules known as the Pauli exclusion rule states that in a given atom no two electrons may be alike in all four of the above elements; in other words two electrons cannot occupy one and the same electronic position within an atom.

This rule carries with it at once a whole group of conclusions which have been reached by piecing together evidence from many quarters. Thus it required that the $K$ shell of all atoms possess two electrons and no more; for since in this shell $n = 1$ and $l = 0$ and hence $m = 0$ it follows from the rule that in the fourth element of their motion, namely the spin, the electrons must be different, and also that not more than two can exist without having two alike in all four elements and hence violating Pauli's rule.

Similarly, and for precisely the same reasons, there can be but two electrons in $s$ orbits in a shell of any total quantum number whatever, and this in turn requires that the eight electrons of the $L$ shell shall be found, two in $s$ orbits and six in $p$ orbits, a relation discovered by Stoner[20] and Main-Smith[21] in England in 1924 by putting together evidence from a variety of sources.

Further, because of the opposite directions of spin of the two electrons of a $K$ shell their joint or resultant moment of momentum and also their total magnetic moment must be zero, which in turn requires that helium be diamagnetic as it is found actually to be, in common with all the noble gases.

Pauli's rule also requires that every closed shell, indeed every completely symmetrical electronic configuration, have a zero value of its resultant moment of momentum, and also of its magnetic moment. This accords with the fact that mercury and other two-valence atoms, in their ground, or unexcited states, are diamagnetic.

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[16] Russell and Saunders, *Astrophys. Jr. 61*, 38, 1925.

[17] Heisenberg, *Zeit. f. Phys. 32*, 841, 1925.

[18] Pauli, *Zeit. f. Phys. 31*, 765, 1925.

[19] Hund, *Zeit. f. Phys. 33*, 345, 1925.

[20] Stoner, *Phil. Mag. 48*, 719, 1924.

[21] Main-Smith, *Jour. Soc. Chem. Ind. 44*, 944, 1925.

Since every completed shell has zero moment of momentum it follows at once that the total or resultant moment of momentum of an atom having a given electronic configuration[22]—and the number of different values that this moment can assume determines of course the number of terms in the fine structure corresponding to that configuration—must be made up of the combined moments of momentum of the electrons in the uncompleted or valence shell. This important relation was first perceived by Russell who also first formulated the new rules for the composition of the total moment of momentum of the atom from the foregoing components. Thus when more than one electron is present in the valence shell the joint orbital moment of momentum $L$ of the whole group is obtained by taking the quantized vector sum of the individual moments $l$. For example, for two electrons in $p$ orbits for each of which $l = 1$ the quantized vector sum is 0, 1, or 2. The physical significance of the fact that the vector sum of the $l$'s is quantized to obtain $L$ is that the electrons are able to rotate only in orbits of such orientations about the nucleus that this vector sum is a whole number of units of moment of momentum. The next step is to obtain the joint moment of momentum $R$ of the spins of the individual electrons. Since these spins are assumed to be in the same plane and each of amount $r = \frac{1}{2}$, the quantized vector sum is here simply the algebraic sum, *i. e.*, in this case

$$R = \frac{1}{2} - \frac{1}{2} = 0 \text{ or } \frac{1}{2} + \frac{1}{2} = 1.$$

Finally to obtain the total moment of momentum of the whole atom we take the quantized vector sum of the total orbital moment $L$ and the total spin moment $R$. This is precisely the quantity which was originally called by Sommerfeld the inner quantum number and designated by the letter $J$. Thus for the values $L = 2$, $R = 1$, the quantized vector sum is 1, 2, or 3.

The fundamental quantum condition is now that all possible values of $J$ constitute a series of which the successive steps differ by unity. If the value of $R$ is an odd number of half units, *i. e.*, if there is an odd number of spinning electrons, then all the values of $J$ are obviously half integral $\left(\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \text{etc.}\right)$ while if the value of $R$ is integral, than all the values of $J$ are likewise integral. The number of possible values of $J$ obtained from a given pair of values of $R$ and $L$ gives the multiplicity, *i. e.*, the number of terms in the fine structure. The maximum of the multiplicity is actually $2R + 1$.

The notation now in general use in the formulation of the new rules is as follows. When the value of $L$ built up as above from the vectorial summation of the $l$'s of the individual orbits is 0, the term is by definition an $S$ term. When $L = 1$ the term is by definition a $P$ term; when $L = 2$ it is a $D$ term; when $L = 3$ it is an $F$ term, etc.

The foregoing quantization rules predict a much larger number of terms than are actually obtained from a given configuration, but Pauli's exclusion rule succeeds in reducing the number of terms to those actually observed.

The new rules thus briefly outlined have had such altogether extraordinary success in predicting the character of the spectra emitted, not only by the simpler atoms such as those which have been the subject of the studies of Dr. Bowen and myself, but by atoms like iron and titanium, thousands of whose lines have already been identified, that it seems as though we now have within our grasp the means of predicting the precise sorts of radiations which can be emitted by all the possible excited states into which any atom can be thrown. Indeed the predictions even of complicated spectra have recently been made so successfully that one prominent spectroscopist has lately remarked that "the heroic age of spectroscopy is already past."

Nevertheless these rules are still to a considerable extent empirical—a remarkable witness to the ingenuity of the physicist in picking out *rules of behavior*, and extrapolating by these rules from observed to unobserved phenomena. They are, however, little more than *rules*. They do not yet represent a logical and consistent scheme of interpretation, and they are only vaguely and very imperfectly translatable into physical pictures visualizable in terms of physical relationships. Thus, after the extraordinary and manifold successes detailed above which followed upon Sommerfeld's introduction of the idea of elliptical orbits—an idea definitely requiring that one unit of azimuthal moment of momentum be assigned to $s$ orbits, two to $p$ orbits, etc.—it is disconcerting in the extreme to find that to fit the new spectroscopic rules $s$ electrons can have no orbital momentum at all ($l = 0$). This looks like a very fundamental contradiction and seems to spoil a whole group of interpretations which were thought to be quite definitely established. It is however just such contradictions which point the way to the next advance, as was so beautifully shown in the foregoing history of the development of the idea of the spinning electron. Furthermore this advance is perhaps already dimly in sight, for it has just been pointed out by Epstein that the new Schroedinger mechanics actually does require that the *s* state (orbit) always represent a pure radial pulsation centrally symmetric, and without any axial structure, and hence without any angular momentum. The whole moment of momentum of electrons in the *s* state would then inhere in the spin. But just what influence this new group of idea is to have upon the whole group of orbital conceptions developed in the early portion of this review is still veiled in obscurity.

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[22] The word configuration as above used means the definite distribution or assignment of the valence electrons to their proper types of orbit, *e. g.*, $s^2\, p^3$ means two electrons in $s$ orbits and three in $p$ orbits. Again $s^2\, p^2\, s$ means that one of the three $p$ electrons, just referred to, has been pushed up into a higher state. Since there is a total of 6 $p$ orbits, 3 electrons can be fitted into the 6 orbits in a considerable number of different ways and to each way corresponds a characteristic term value.

The last fourteen years of the history of spectroscopy, however, constitutes a remarkable illustration, first, of the rapidity of our modern rate of advance—a whole huge domain, a veritable dark continent having been explored and reduced to order and civilization in a period of less than fifteen years; and second, of the power of the physicist's two tools, analysis and experiment, when used properly together, for forcing open nature's most tightly barred and bolted doors and wresting her most jealously guarded secrets from her for the enrichment of the life of future generations; for every bit of added knowledge of nature adds so much to our control over her, that is, to our ability to turn her hidden forces to useful ends.

# Influence of Internal Vacua and Ionization
## on the Life of Paper Insulated High-Tension Cables

BY ALEXANDER SMOUROFF[1] and LEO MASHKILEISON[2]

Fellow, A. I. E. E. Associate, A. I. E. E.

***Synopsis.**—At the end of the year 1926 the High-Voltage Laboratory of the Electrotechnical Institute in Leningrad undertook an experimental research in order to study the influence of internal vacua and ionization on the life duration of paper insulated high-voltage cables, as well as to clear up the conditions under which such vacua may occur.*

*W. A. Del Mar[3] drew attention to the importance of internal vacua in high-voltage cables and pointed out the three probable causes of their appearance, namely:*

*1. Temperature changes after installation of the cable, which produce a change of volume of air and oil in the cable in view of the different thermal expansion coefficient of lead and insulation of the cable.*

*2. Residual deformations, occurring when the cable is put on a reel and taken off it afterwards.*

*3. Changes in chemical structure in the impregnating compound under the influence of ionized air, which produce a decrease of volume of the compound.*

*The aim of the research was to clear up the part of the above mentioned causes in the formation of internal vacua, then to determine the values of those vacua and the decrease of life duration of the cable under the influence of the latter.*

*The research is not yet finished and only its preliminary results are reported on these pages.*

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### OBJECT OF INVESTIGATION

As an object of investigation a high-voltage cable was taken, the design of which is reproduced in Fig. 1.

The cable consists of three cores, each having a thickness of insulation of 10 mm. (25/64 in.) and each covered with a lead sheath. The three cores are wound together into a three-phase cable and are protected by a double steel ribbon armor. The working pressure of the cable is 35 kv. with grounded neutral and the working pressure for each phase is 20.2 kv. The conductor of each phase is split into two concentric stranded conductors. The inner conductor serves for cable protection by the Lypro system.

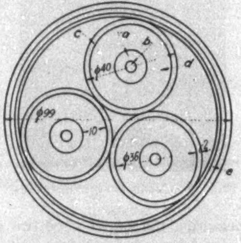

FIG. 1—CROSS-SECTION OF 35-KV. CABLE USED IN TESTS

- a. Outer copper conductor
- b. Inner conductor for Lypro cable protection
- c. Lead sheath
- d. Paper insulation
- e. Double steel ribbon armor

The tests were made with single conductors of the cable having a length of 10 m. and with grounded lead sheath.

### CONDITIONS OF TESTS

During the performance of tests chief attention was drawn: (1) to the control of internal vacua, (2) to the electric field design on the end of cables under tests, and (3) to the elimination of the cable end influence during loss measurements.

The ways of propagation of air in the cable were studied in order to work out the best method of control of the internal vacuum in the cable. For this purpose different methods of pumping the air out of the cable and of the manometer connections were tried. These tests showed that the propagation of air in the cable takes place chiefly along the stranded core in the inner part of it and immediately on its surface.

The insulation of the cable presents in most cases a medium quite impenetrable for air. Air can be concentrated in single bubbles between the insulation and the lead sheath, but it cannot propagate along the cable. In view of these facts the pumping out of the cable of air was made from one of its ends and the internal vacuum was controlled by two manometers connected with both ends of the cable.

In most cases the same pressure on both manometers connected with both ends of the cable was established during a few seconds. But in certain special cases obstacles were found in cables which prevented the longitudinal propagation of air.

As previously mentioned, the insulation of cables presents a medium quite impermeable for air. But in certain cases air may be propagated from the conducting core to the lead sheath by bifurcated paths between the sheets of paper strands of the insulation. This explains the leakage of air through the insulation of the cables'

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[1] Professor at the Electrotechnical Institute of Leningrad.

[2] Electrical Engineer and Teacher at the High-Voltage Laboratory of the Electrotechnical Institute in Lenigrad.

[3] William A. Del Mar, *The Effect of Internal Vacua Upon the Operation of High-Voltage Cables.* A. I. E. E. TRANS. 45, 1926, p. 572.

*Presented at the Winter Convention of the A. I. E. E., New York, N. Y., February 13-17, 1928.*

ends, for the performance of tests necessitated the taking off of the lead sheath on the ends of the cable on a length of 1 m. In some cases the leakage was so considerable as to make difficult the maintenance of a constant vacuum in the cable. The control of the electric field on the ends of the cable was accomplished by means of end insulation, schematically shown in Fig. 2 and on the photograph Fig. 3.

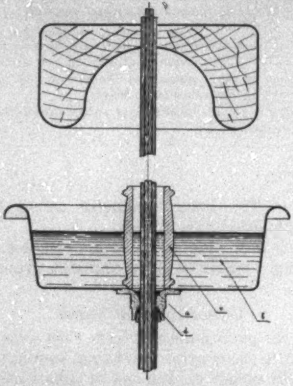


Fig. 2—Cross-Section of Cable Terminal

a. Hemp packing
b. Transformer oil
c. Porcelain bushing
d. Stuffing box

Fig. 3—Cable Terminal

The upper electrode was made of wood and its surface was covered with tin-plate. The lower electrode is metallic.

On Fig. 2, *a* is a hemp packing, *b*, transformer oil, *c*, a procelain bushing, and *d*, a stuffing-box. The test of such a cable end insulator showed that its spark-over voltage is about 130 kv. This design of the cable end insulator provides quite a satisfactory form of the electric field on the ends of the cable, so that the breakdown of the cable during the tests occurred always somewhere in the middle of the cable, but not on its ends. If the curvature of the stuffing-box were made not along the arc of a circle, but along another more suitable curve, the spark-over voltage of such a cable end insulator could be noticeably increased without increase of its dimensions.

The elimination of the influence of cable ends on the measurement of losses in the cable was performed in the following way. At a certain distance from the ends of the cable two circular grooves 2 mm. wide were cut whereby the lead sheath was divided into three parts. The middle part was connected to Schering's bridge for measuring the loss and the two outer parts were grounded and formed guard rings.

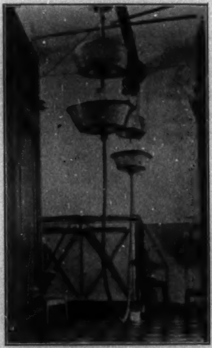


Fig. 4—Cable Ready for Test

After the sample of the cable was prepared for the tests, the cable was hung on two strings of insulators, as shown in Fig. 4.

The test voltage was derived from three Koch & Sterzel transformers, 0.5/125 kv., which could be connected in series. The voltage control was effected by means of a potential regulator made by the same firm. The study of the voltage curve of the potential regulator showed that when the latter was fed from 500 volts, a sinusoidal curve was obtained with one transformer only for voltages above 47 kv. If the potential regulator was fed at 110 volts, its voltage curve proved to be sinusoidal also. Therefore, for voltages under 50 kv., the potential regulator was fed at 110 volts and three high-voltage transformers were put in series. For voltages above 50 kv. the potential regulator was fed at 500 volts and only one high-voltage transformer was used.

In all these cases, the voltage curve was of a good sinusoidal form, as indicated by oscillograms.

Dielectric loss measurement was made by means of a Schering bridge. The air standard condenser was of a flat type with three plates, the middle of which was connected to the high-voltage winding of the transformer. The working surface of the plates (without guard rings) was equal to 17,840 cm.$^2$ The distance between the plates could be changed in such a way that even for very low voltages, about 3 kv., the power factor could be accurately measured to three significant figures.

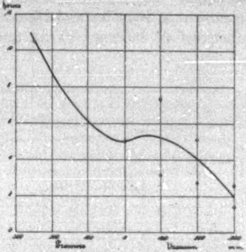


FIG. 5—VARIATION OF CABLE LIFE WITH PRESSURE AND VACUUM AT 60 KV.

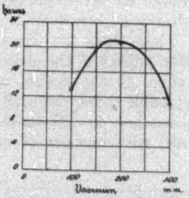


FIG. 6—VARIATION OF CABLE LIFE WITH VACUUM AT 50 KV.

To clear up probable errors in the measurement of losses, phase displacements in the resistors were measured by means of a compensation method. This was also done with the parasitical capacities (capacity of the connecting conductor of the bridge and the capacity of the non-inductive resistances). These measurements showed that the largest probable error does not exceed a few seconds of phase displacement.

During the loss measurements the bridge was controlled in the following manner. After a measurement of the loss angle in the cable, a known non-inductive resistance $R_0$ was put in series with the latter and the loss angle was again determined. For a voltage $E$ and a capacity $C$ of the cable the loss in the non-inductive resistance can be calculated as follows:

$$J^2 R_0 = E^2 \omega^2 C^2 R_0$$

This loss must equal the difference of losses measured in the two cases mentioned above. Agreement between the results of measurement and calculation indicates normal operation of the bridge. Such a proof of the bridge was made several times and always presented quite satisfactory results.

## LIFE DURATION OF CABLE IN FUNCTION OF INTERNAL VACUA

For the determination of the life duration of the cable in function of internal vacua, different vacua were created in the interior of the cable and the latter was put under different voltages. During each test the vacuum and the voltage were held constant and the lapse of time was noticed, until breakdown of the cable occurred. As it was impossible to close the ends of the cable hermetically, as already pointed out, it proved necessary to renew the vacuum periodically. This was done without taking off the voltage. The permitted variations of the vacuum were ± 5 mm. barometric pressure. But in several cases, when the leakage of air through the cable insulation was small, after the voltage was put on the cable, an increase and not a decrease of the vacuum was observed. This can probably be explained by chemical changes occurring in the impregnating compound under the influence of

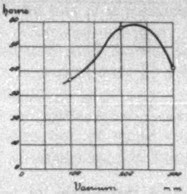


FIG. 7—VARIATION OF CABLE LIFE WITH VACUUM AT 42.6 KV.

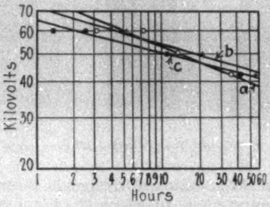


FIG. 8—VARIATION OF CABLE LIFE WITH VOLTAGES AT DIFFERENT VACUA

a. 100 mm. vacuum
b. 200 mm. vacuum
c. 300 mm. vacuum

ionized air and accompanied by a volume decrease of the compound, as suggested by item 3 of the synopsis.

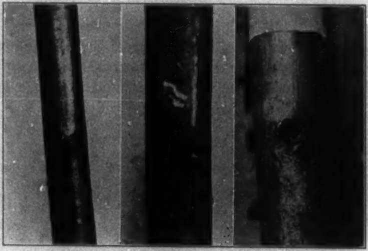
The chief results of tests of life duration of the cable under different vacua and voltages are given in Table I. On Figs. 5, 6, and 7 are drawn curves giving the life duration of the cable under different voltages in function of vacua, and the curves in Fig. 8 give the life duration under different vacua in function of the impressed voltage.

TABLE I

| Voltage, kv. across 1 cm. of dielectric | Vacua in mm. of mercury column (under the atmospheric pressure) | Pressure in mm. of mercury column (over the atmospheric pressure) | Life duration in hours |
|---|---|---|---|
| 60 | .. | 250 | 10.5 |
| 60 | 0 | 0 | 5 |
| 60 | 100 | .. | 5.2 |
| 60 | 200 | .. | 4 |
| 60 | 300 | .. | 2 |
| 50 | 100 | .. | 13 |
| 50 | 200 | .. | 21 |
| 50 | 300 | .. | 11 |
| 42.6 | 100 | .. | 36 |
| 42.6 | 200 | .. | 57.7 |
| 42.6 | 300 | .. | 41 |

The character of the places of breakdown of the cable is shown on Figs. 9, 10, and 11.

The study of curves on Figs. 5-8 shows the surprising fact that to each voltage corresponds a certain most advantageous vacuum, at which the life duration of a cable becomes a maximum, which is very sharply pronounced at voltages of 50 and 42.6 kv. and less sharply at a voltage of 60 kv. To check this fact, duplicate cables were tested and the results obtained showed a satisfactory agreement with the statement mentioned above. This would suggest the idea that this cannot be explained by lack of uniformity of the cable samples.



FIGS. 9, 10, 11—BREAKDOWN POINTS OF CABLE

In addition to this it may be seen from the curves on Figs. 5-8 that the vacuum for which the life duration of the cable has its greatest value depends upon the voltage. With increase of voltage the maximum becomes smoother and is displaced in the direction of lower vacua.

## DIELECTRIC LOSSES IN THE INSULATION OF THE CABLE IN FUNCTION OF THE INTERNAL VACUA IN THE LATTER

In order to make a more complete analysis of the influence of vacua on life duration of the cable and to clear up the phenomenon of an optimum vacuum, measurements of loss angles were made at different voltages and for different vacua and pressures in the interior of the cable. The results of these measurements are given in curves of Figs. 12 and 13 which show the losses as functions of internal vacua and pressures.

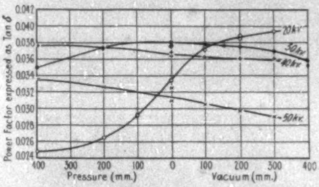


FIG. 12—RELATION BETWEEN POWER FACTOR AND INTERNAL PRESSURE

The vacua are drawn in the positive direction of the axis of abscissas and the pressures in the negative direction.

In Figs. 14 and 15 are drawn curves showing losses for different voltages as functions of different vacua and pressures. These losses are expressed as tangents of the imperfection angle δ of the dielectric. These are approximately equal to the cosines of the angle of lead for ordinary cable dielectrics such as those under consideration.

As we may see, with increase of voltage, *t g* δ increases, reaches a maximum value, and then decreases. The maximum of *t g* δ is reached at a lower voltage as the internal vacuum becomes greater. The variation of the value of *t g* δ is least in proximity to the maximum.

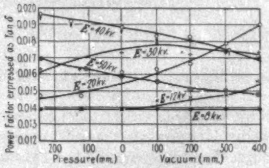


FIG. 13—RELATION BETWEEN POWER FACTOR AND INTERNAL PRESSURE

An explanation of the decrease of power factor with increase of voltage was given by C. L. Dawes and P. L. Hoover.[4] With an increase of voltage after all the air in the cable has been ionized, the potential gradient in this air does not depend upon the voltage but equals the breakdown gradient of air. Hence it follows that the loss in air at any further increase of voltage will remain constant and the total loss in the cable will increase more slowly than in proportion to the square of voltage, *i. e.*, $t\,g\,\delta$ will decrease.

Assuming the loss angle of the dielectric proper (*i. e.*, without air) to have a constant value and neglecting the small variations of capacity of the cable at increase of voltage, it is possible to determine the loss angle of the entire insulation (*i. e.*, including air) for voltages higher than the voltage $E_0$, which corresponds to the maximum value of $t\,g\,\delta = t\,g\,\delta_0$, if we know the loss angle of the insulation proper, $t\,g\,\delta$.

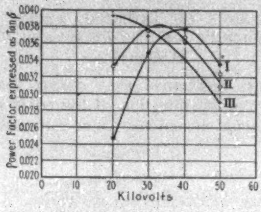


Fig. 14—Relation Between Power Factor and Internal Pressure

I. Pressure 400 mm. over atmosphere
II. Atmospherelc pressure
III. Vacuum 300 mm.

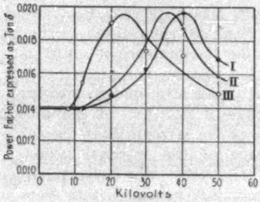


Fig. 15—Relation Between Power Factor and Voltage

I. Pressure 250 mm. over atmosphere
II. Atmospheric pressure
III. Vacuum, 400 mm.

In effect the loss in air for a voltage $E > E_0$ may be expressed as follows:

$$P_1 = E_0^2\,\omega\,C\,(t\,g\,\delta_0 - t\,g\,\delta_1) = \text{const.}$$

The loss in the insulation at a voltage $E$ will be:

$$P_2 = E^2\,\omega\,C\,t\,g\,\delta_1$$

Therefore the total loss will be equal to:

$$P = P_1 + P_2$$

$$= E^2\,\omega\,C\left[\left(\frac{E\,o}{E}\right)^2(t\,g\,\delta_0 - t\,g\,\delta_1) + t\,g\,\delta_1\right] = E^2\,\omega\,C\,t\,g\,\delta$$

Thus

$$t\,g\,\delta = \left(\frac{E\,o}{E}\right)^2(t\,g\,\delta_0 - t\,g\,\delta_1) + t\,g\,\delta_1$$

The curve drawn on Fig. 16 gives the loss in the cable as a function of the applied voltage at atmospheric pressure. The dotted curve gives the values of $t\,g\,\delta$, as calculated from the above formula. As may be seen, there is fairly good agreement between the calculated and experimental curves.

The curves on Figs. 12 and 13 show that a certain vacuum at which the loss is a maximum corresponds to each voltage. After the maximum is attained the loss begins to decrease and the velocity of decrease of the loss at first is greater then at a further increase of the internal vacuum.

With increase of voltage, the maximum loss is displaced in the direction of small vacua and consequently we find displaced in the same direction the parts of curves with diminished loss variations. Thus we have a relation of the same character as that already mentioned, between the life of the cable and the internal vacua. This similarity shows that there is something in common between the two phenomena and suggests the ways for explanation of the nature of the phenomenon of the optimum life vacuum.

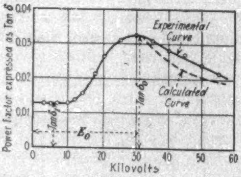


Fig. 16—Comparison of Calculated and Experimental Curves Between Power Factor and Voltage Above the Voltage of Maximum Power Factor

A complete explanation of this phenomenon was not yet found, but it is possible that its cause may be as follows.

With an increase of the internal vacuum in the cable at a constant voltage, (beginning from large pressures of the internal air at which the air is not yet wholly ionized), the loss will increase at first. Then with a vacuum, at which the internal air is wholly ionized, the loss will attain its maximum value. With a further increase of the internal vacuum the loss will decrease, as the dielectric strength of air will decrease and therefore the voltage drop across the air will also decrease. As the dielectric loss will heat the cable, the temperature

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4. C. L. Dawes and P. L. Hoover, *Ionization Studies in Paper Insulated Cables*, A. I. E. E. Trans., Vol. 45, 1926, p. 141.

of the latter will vary approximately in the same manner as its dielectric loss.

As the life duration of a cable must naturally decrease with an increase of hot-spot temperature, it should at first decrease with an increase of the vacuum, and then increase. With increase of the vacuum, however, because of the decrease of voltage drop through the air, the gradient of the electric field in the insulation of the cable must increase. In the same way, the tangential components of the gradient along the joints of paper strips of insulation must also increase. All these causes provoke a continual decrease of the life duration of a cable with increase of the vacuum. For instance the fact that the life duration becomes five times less, at a voltage of 60 kv. with a change of conditions of the internal air in the cable from a pressure of 250 mm. (over atmospheric pressure) to a vacuum of 300 mm., suggests that in general the dielectric strength of a solid insulation may depend upon the pressure of the surrounding air. In a cable it is quite possible that the barrier or baffle properties of the insulating paper become inferior and a freer motion of ions begins in the latter.

Thus we see that with an increase of vacuum, at first all causes tend to provoke a decrease in the life of the cable. Then, when the loss and consequently the temperature begin to decrease, their influence may become predominant in comparison with all other causes and the cable's life will begin to increase. With a further increase of vacuum, the rate of variation of losses, as stated above, will diminish. This will lead to a state when the influence of causes decreasing the cable's life will predominate.

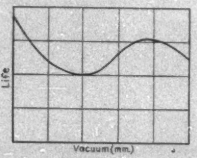

FIG. 17—TYPICAL LIFE-VACUUM CURVE AS SUGGESTED BY POWER FACTOR AND VACUUM RELATION

This analysis shows that the curve giving the influence of the vacuum on a cable's life duration must be of *s* shape shown in Fig. 17. This curve has the same shape as that obtained by experiment for a voltage of 60 kv. and reproduced in Fig. 5. For the other two experimental curves drawn on Figs. 6 and 7, we have only the parts containing the maximum, as these were not determined over a wide range of pressures. The fact that the maximum becomes smoother with an increase of voltage can be explained in the following way; at high voltages, the gradient in the insulation of the cable and the tangential components of the gradient become of prevailing importance, for, at high voltages, when the air is wholly ionized, the losses decrease with an increase of vacuum and the influence of their decrease at an increase of the vacuum becomes less perceptible.

At the working voltage of the cable, the optimum vacuum as it appears will be so considerable that it will be practically necessary to take into consideration only the decrease of the cable's life.

### THE APPEARANCE OF INTERNAL VACUA IN CABLE IN CONSEQUENCE OF CHEMICAL AND THERMAL ALTERATIONS

It has been mentioned that during the tests for determining the life duration of the cable in function of internal vacua, a tendency to an automatic increase of the vacuum was observed, as it seems under the influence of chemical alterations in the impregnating compound under the influence of ionized air.

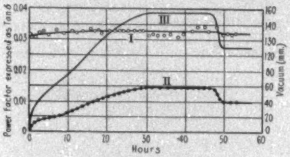

FIG. 18—CHANGE OF VACUUM AND POWER FACTOR AS RESULT OF PROLONGED LIFE TEST

I. Power factor
II. Observed vacua
III. Vacua corrected for parasitical volumes

To study this phenomenon quantitatively, a piece of cable was put under atmospheric pressure of air on its working voltage of 20.2 kv. A manometer was connected to one of the extremities of the cable to observe the appearance of the internal vacua. The other extremity of the cable was hermetically closed. At the same time, loss measurements were undertaken. The curves in Fig. 18 reproduce the results of the experiment. The curves are: I, the loss curve; II, the curve of observed vacua; and III, the curve of vacua, which would happen if there would not be connected to the cable the parasitical volume of air in the leads of rubber tubes and in the manometer.

The sudden decrease of vacuum at the end of the experiment can be explained by imperfect sealing of the cable.

The volume of air, which it was necessary to know to plot curve III, was measured by applying to the interior of the cable, a known volume of air at atmospheric pressure and observing the change of the vacuum after its introduction into the cable.

It is obvious from curve III that under the working voltage of the cable, vacua approximating 155 mm. of mercury may appear.

For the determination of internal vacua which can appear under the influence of temperature changes, a piece of cable was heated to a temperature about 40 deg. cent., measured by a thermometer dropped to the core of the cable.

The cable was heated with an electric current about 800 amperes. After the heating current was interrupted, in a lapse of time, which allowed to attain a comparatively uniform distribution of temperatures in the interior of the cable, the latter was hermetically closed and connected to a manometer.

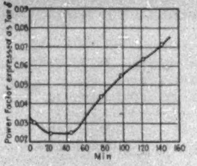

Fig. 19—Relation Between Power Factor and Life on a Cable which Failed in 157 Min.

In this way it was found that at a decrease of temperature in the cable of 25 deg. cent. the internal vacuum increased to 180 mm. of mercury (corrected for the parasitical volume in leads of rubber tubes and the manometer).

## Losses in Cable as Function of the Duration of Voltage Application

Loss measurements in the cable were made at the same time as life duration of the cable as a function of the internal vacua was determined.

Characteristic curves of power factor as function of applied voltage obtained during these tests are reproduced in Figs. 19 and 20. As may be seen from these curves, $t\,g\,\delta$ at first diminishes, then remains constant for a time, and then increases until breakdown of the cable occurs.

The decrease of $t\,g\,\delta$ during a certain time after the application of voltage may be explained by the heating of the cable through the dielectric losses. The ambient temperature was about 15 deg. cent. and as the cable losses have a minimum at a temperature about 40 deg. cent., as shown by Mr. P. Dunsheath,[5] the heating of the cable leads to a decrease of $t\,g\,\delta$. After establishing a thermal equilibrium, $t\,g\,\delta$ remains constant for a certain period. This shows that the chief causes of the breakdown in the cable are chemical alterations, not pyroelectric effects.

If breakdown in the cable were due to thermal causes, we should have a continual rise of temperature in the cable and the loss curve would not have its horizontal part. The pyroelectric effect begins to play an important part only at the approach of the cable's breakdown, which accounts for the appearance of hot spots before the breakdown.

## Conclusions

1. Internal vacua of the order of 350-400 mm. of mercury may appear in a cable under the influence of temperature changes and ionization of air.

2. The appearance of internal vacua at the working voltage of a cable may noticeably lower the life duration of the latter.

3. Air can easily propagate along the core of a cable and in the interior of the latter, but on considerable lengths of cable stoppers may occur, which will impede such a propagation.

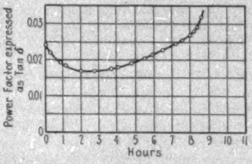

Fig. 20—Relation Between Power Factor and Life on a Cable which failed in 10 hr. 29 min.

4. To prevent the dangerous effect of internal vacua the following measures may be recommended:

a. Use of chemically stable compounds;

b. Arrangement of free ducts in the interior of the cable for air to maintain the atmospheric pressure in the interior of the cable by using the flow of air from the extremities of the cable;

c. Arrangement of free air ducts in the interior of the cable and in the splices for compensation of vacua that may appear with the volume of air contained in them;

d. Pumping of dry air through ducts in the core of a cable to maintain the pressure in the cable higher than that of the atmosphere;

e. Filling a cable with transformer oil forced under pressure at the splices of a cable to provide compensation at volume changes of internal air in the cable.

## Discussion

**W. A. Del Mar:** This paper has been very interesting to me because we tried in the laboratory of the company with which I am connected to do this work several years ago, and encountered very serious experimental difficulties. We found great difficulty in maintaining the vacua at the ends of the cable without weakening the terminals, so that the terminals, rather than the cable, would fail. We made a great many break-down tests, but none of the results ever reached the point where we could bring them before the Institute for discussion. Yet there was a very definite indication that there was a connection between the internal pressure of the cable and the life. For instance, five cables were tested with a vacuum of about 24 in., and the average life of those cables was 20 hr. Similar cables were tested at the same voltage at atmospheric pressure and the average life was 274 hr. When we came to analyze these individual results there was not a single one that was really conclusive. Something happened in every test, either the vacuum line became clogged, or we were not sure that the pressure was the same at the two ends of the cable, or else the terminals failed. We made repetitions of these tests and ran into similar difficulties, and by the time we had just about reached the point where we believed we had solved the terminal problem we were obliged to stop the work and go on to something that was then more important. It was therefore very gratifying to see these Russian experimenters take up the work.

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[5] P. Dunsheath, "Dielectric Problems in High-Voltage Cables," *Journal* of the Institution of Electrical Engineers, January, 1926.

Since the presentation of my paper in 1926 on *Vacua in Cables*, a number of pertinent observations and tests has been made, but more problems have been raised than solved.

The application of reservoirs of oil to cable joints to compensate for pressure changes due to expansion and contraction of cable compound has become standard practise for voltages above 20,000, but certain observations to date suggest that cable may have an unexpectedly large capacity for absorbing oil from the reservoirs. The questions naturally arise—how long will this appetite last and where is the oil going? Observations, theory, and common sense seem to support one another in explaining this.

When a cable cools, the oil contracts into the spaces of high surface tension, that is, between tape surfaces if the tapes are tight, and leaves voids in the correspondingly thick helical spaces between abutting tape edges. These helical spaces are from 5 to 8 mils thick, about 1/32 in. wide, several hundred ft. long in an operating length of cable, and partially clogged with compound. A pressure of a few pounds per square inch, applied at the ends of the channels, has little or no effect, and the channels fill only by slow capillary action which is interrupted during the high-temperature periods of the heat cycle.

On the other hand, when a cable heats, the oil expands into the edge spaces and when they are filled, exerts pressure both along the helical columns of oil, and radially, the latter tending to stretch the sheath as the long helical columns of oil cannot be moved by pressure. Hence in every heat cycle oil is absorbed into the cable by capillarity during contraction and not driven out during expansion. This goes on until the space between the lead and core has grown sufficiently large to permit the compound to flow in response to the daily heat cycles. When this has occurred, the oil reservoirs will alternately fill and empty as the temperature changes.

If the paper tapes are applied so loosely that the capillarity between tapes is substantially equal to that in the edge spaces, contraction will occur more or less uniformly and the contracted compound, instead of disposing itself between tapes, will remain a continuous mass and will transmit pressure hydrostatically over a considerable distance. Hence, such a cable, when cooled, will not absorb oil from the reservoirs by capillarity as there are no long capillary filaments, the vacuum being distributed in bubbles, and when heated will merely experience a collapse of the bubble voids as the oil expands into them.

Cables made to pass such specifications as those of the Association of Edison Illuminating Companies or the National Electric Light Association, belong to the tight category. The pre-specification cables which gave such excellent service when not loaded to the point of accumulative heating, were of the loose category. The same applies to the best European cables, or many of them. For instance, one European cable which has proved its merit in high-voltage service is so loose that the oil-to-paper ratio, by weight, is 1.3 or about 50 per cent greater than a specification cable of American make. Such a cable does not absorb appreciable oil from the splice reservoirs. It responds to a certain extent to the heat cycles but the total absorption of oil over a long period is very slight.

The cable which was used by the Russian experimenters is very different from our American cable because the life of the former is very low, thus making it easier to obtain cable rather than terminal failures. It would be interesting if the authors could tell us something about the characteristics of that cable, what the proportion was of oil to paper, and so forth. I believe the whole research in its completed form will be looked forward to with interest by all of us who are interested in this cable problem, the problem of cable pressures.

**C. L. Dawes:** The authors describe a method of verifying the accuracy of their bridge. They state: "After a measurement of the loss angle in the cable, a known non-inductive resistance $R_0$ was put in series with the latter and the loss angle was again determined."

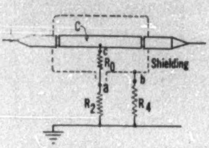

FIG. 1

The $I^2 R_0$ loss in this resistance $R_0$ is then calculated and compared with the increased loss as measured with their bridge. It would have been instructive if some quantitative data on these measurements had been given.

We have experimented considerably with this type of measurement and find that it must be done with considerable care. For example, in Fig. 1 herewith is shown a sample of cable with the customary shielding around the test portion of the sheath. The added series resistance $R_0$ is shown within the shielding. If the shielding ($b$) and point $a$ are brought to the same potential by means of $R_4$, as is usually done, there will be a difference of potential between points $b$ and $c$ equal to the voltage drop in $R_0$, which may be of the order from 50 to 200 volts. This produces a considerable differential of potential between the cable sheath and its shielding. Since the capacitance between sheath and its shielding ordinarily is comparatively large, considerable error, due to shunted capacitance, may result.

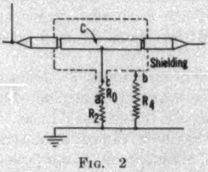

FIG. 2

This difficulty may be avoided by connecting the resistance $R_0$ outside the shielding, as shown in Fig. 2. $R_0$ must be mounted so that its capacitance to its surroundings is small. Then points $c$ and $b$ must be brought to equality of potential by adjusting $R_4$. The sheath and its shielding, between which the capacitance is large, are now at the same potential. There is a difference of potential now between $R_0$ and the shielding, which will result in considerable error, unless the capacitance between $R_0$ and the shielding is made small. There are so many other aspects to this and related problems that I have described them in a paper, which I hope to present before the Institute in the near future.

The authors state that after the air in the cable has become ionized, the voltage in the air becomes equal to the voltage gradient of the air which is constant. That is, this voltage gradient then becomes practically constant, independent of further increase of voltage across the cable. This statement is based on results given in a paper by P. L. Hoover and myself to which reference is made. They further state: "Hence, it follows that the loss in air at any further increase of voltage will remain constant . ." They then derive an equation giving the variation of power factor with voltage, based on this assumption. This assumption, and hence the resulting equation, I believe, is in error. Investigations which we are now making show that after the ionization voltage is reached, the power loss becomes practically a linear function of further increase of voltage, and thus is not constant. This relationship may also be derived from curves given in Appendix IV of the paper by P. L. Hoover and myself, to which reference is made.

The authors give an explanation of the variation of life with pressure, based on the changes with pressure and voltage gradient of the losses in the air spaces, tangential components of gradient, etc. Among other reasons, they suggest that the barrier action of the insulating paper may be a function of the pressure.

For the heavy positive ions the mobility is inversely proportional to the pressure. With reduction of pressure, this tends to increase the energy of each impact. On the other hand, the voltage gradient is probably inversely proportional to the pressure, which reduces the energy of impact. Also, the number of ions available is inversely proportional to the pressure. Since the current is constant, this effect must, however, be offset either by increased ionic velocities or by a more rapid recombination which can easily occur in these restricted air spaces. Hence the net bombarding action of the positive ions probably does vary with pressure, and it is possible that its effect may be a maximum at some particular pressure, resulting in a shorter life at that pressure, as suggested in the paper.

Although some of the data and conclusions drawn by the authors are open to criticism, I feel that on the whole the paper is a contribution to our knowledge of cable phenomena, and it is particularly valuable in that it suggests a broad field for further research along these particular lines. Their attempts to reconcile power-factor variation, hours life, etc., with the behavior of ionized gas in restricted spaces is also a step in the right direction. The authors have undertaken a difficult task in making measurements of pressure, voltage, power, etc., simultaneously. The necessity of protecting the ends from flashover and yet sealing them against pressure adds to the difficulties.

**W. F. Davidson:** There are two points I should like to mention.

One is in connection with the arrangement of the cable for measuring power factor and dielectric loss. Referring to Fig. 4 it is noticed that the cable is suspended in the air with no apparent provision for shielding that part of the sheath which is used for the test electrode. I think that everyone who has attempted measurements of this sort will appreciate the possible considerable error here; that is, the cable will tend to pick up stray charges, and quite possibly these will be of sufficient magnitude to influence the results.

The other consideration is in connection with the method of checking the bridge and in several other cases. For some time I have been making efforts to determine the form of current wave obtained in cases where we suspect ionization to occur, as at the higher voltages considered by the authors. Our tests are not complete, but indicate that the distortion may be sufficient to introduce errors if we speak of "power factor" in the sense that implies a phase relation between simple harmonic components. The problem is even further complicated by the fact that many of the components of distortion seem to be haphazard at high frequency rather than simple overtones. Consequently, losses computed from bridge measurements are open to question, and likewise theories based on these losses.

**E. H. Salter:** The final test of the correctness of our theories in regard to the deleterious effect of void spaces in cable insulation is the life of the cable. None of our accepted tests of cable will tell us definitely what the life—or even the probable life—will be. The test that gives us the most information on this point is the accelerated life test. While the conditions under which that test is made may have considerable effect on the results, still it gives us more reliable information as to the probable performance of cable than anything else. The authors are to be commended not only for undertaking a study of one of the most important problems confronting high-voltage cable users today, namely, what is the actual effect of internal voids, ionization, etc., on the life of cable, but also for studying the effect by means of life tests—the nearest thing to an actual service test—rather than by indirect tests based on theoretical deductions.

From the standpoint of one interested in comparative tests of cable of domestic manufacture there are several points of interest in this paper. Apparently the cable used for this investigation was of decidedly inferior quality. This conclusion is drawn from the following comparisons with normal cable of domestic manufacture:

a. The test at 60 kv. (Fig. 5) corresponds to approximately 155 volts per mil thickness of insulation (average stress gradient). At this voltage Fig. 5 shows the life to vary from 10.5 hr. with an internal pressure of 250 mm. of mercury above atmosphere to only 2 hr. with a vacuum of 300 mm. of mercury. At atmospheric pressure the life is shown as 5 hr. The average life to be expected from normal domestic cable tested at this voltage (155 volts per mil), and at pressures approximating atmospheric, is 700 hr., or about 140 times as long as shown in Fig. 5.

b. The relation between power factor and voltage is shown in Fig. 15. Here it is noted that the power-factor—voltage curve at atmospheric pressure reaches a maximum at about 37 kv., indicating that at that voltage ionization of the "void spaces" in the cable is complete. This voltage corresponds to only about 95 volts per mil of insulation (average stress gradient). In the normal domestic cable of this type ionization is not complete at voltages as high as 300 to 400 volts per mil, and in many cables has not even started at voltage gradients of the order of 95 volts per mil.

c. The cable tested was essentially high-loss cable, thus accounting for the increase in the power-factor—time curves shown in Figs. 19 and 20. Normal domestic cables of this type which have a power factor of about 0.5 per cent at 25 deg. cent. show no increase in either power factor or temperature with approaching end of life at voltages corresponding to those used in these tests.

Little mention is made of the manner of producing the pressures and vacua in the cable samples. However, what is said seems to indicate that these conditions were obtained by pumping air into, or out of, the cable. Pressure changes obtained in this manner correspond to different quantities of air in the cable, whereas in a cable in service the amount of gas present is substantially constant, pressure changes being produced by expansion and contraction of the solid and liquid components of the cable.

The fact that each pressure or vacuum in these experiments corresponds to a new and different quantity of air in the cable may affect the shape of the life *vs.* pressure curves shown in Figs. 5 to 7.

The measurement of these internal pressures and vacua requires many precautions. As indicated in Fig. 18 the correction to be applied for parasitic volumes of air in the manometer tubing, etc., may be many times the actual pressure reading. These corrections are likewise difficult to determine, especially where rubber hose, which will expand or contract with pressure changes, is used for connections. The use of a solidly connected monometer (no rubber tubing) with the lead tube filled with oil, read by bringing the mercury column always back to the same zero (no change in volume in the leads) should eliminate these corrections and their attendant errors.

The cable used in this series of tests consisted of the individual conductors of a length of three-conductor shielded-type cable. Since this is only a preliminary report, it is hoped that the findings may be augmented by similar tests on not only other types of cable, but also cable having a quality nearer that of cable now being made.

**H. Connell:** The company with which I am connected has been actively engaged in cable research for about a year and a half. Some of the results we have obtained, which have not as yet been published for public distribution, would lend an interpretation to the data the authors present completely different from that at which they have arrived. Therefore, while I complete disagree with their conclusions, I do not in the least mean to belittle their work.

In the first place I do not believe that the fact that they obtained like pressure readings at opposite ends of the core justifies their conclusion that that pressure represents the pressure throughout the insulation. Our experiments indicate that pressure transfer through or even along cable insulation is a slow business. Further, such pressure transfer is very markedly a function of temperature, and at temperatures less than 60 deg. cent., days and even weeks are required, at least in the case of the 3-conductor cables with which we experimented. Our pressure measurements have been made with ordinary gages oil-filled, wiped to the sheath, and with a tube extending to the center filler. In one case we had a 90-ft. length of cable arranged so that we could circulate current through it to heat it. The ends were sealed and a sylphon filled with spindle oil was connected to one of them. The sylphon was so loaded as to maintain a pressure of about 2 lb. per sq. in. On a heating cycle selected to reproduce actual service conditions we had pressures of 25, 32, and 56 lb. per sq. in. at respective distances of 21, 43, and 89 ft. from the sylphon. With decreasing current the corresponding vacua were 10, 18, and 7 in. of mercury respectively. These vacua remained sensibly unchanged for 10 hr., at which time the heating cycle was increasing the temperature again.

Our experiments on pressure transfer in a radial direction through the insulation are not as yet complete. However, preliminary results indicate that it is very slow indeed.

The terminal design used by the authors is very nice. There is every reason to believe the loss measurements indicate a value very close to the absolute value. The method of eliminating end losses is very clever.

I do not feel that the curves in which breakdown is concerned can be taken as anything more than a general trend. Breakdown in even the simplest of dielectrics is an erratic business.

The authors comment on the fact that the measured power factor in Fig. 16 lies, for high voltages, above the calculated value. This indicates to my mind that as the voltage is raised above that value giving greatest power-factor, pockets of gas which were too small to ionize at the lower voltage, ionize progressively, and thus give increased loss.

Our experiments have led us to believe that there is no reaction into which cable compounds enter, which operates to reduce their volumes materially. We further believe that there is no reaction other than oxidation in which cable compound absorbs gas during conditions similar to those under which the authors took the data for Fig. 18. We suspect that in connecting and testing their manometers they displaced sufficient compound throughout the strands of the conductor to establish a continuous air path. Upon the application of high voltage this air became ionized and activated. Under such conditions the oxygen of the air reacted chemically with the compound. The corrected vacuum curve of Fig. 18 is exactly what one might expect if such were the case. The curve has a perfectly flat top. In our explanation this is caused by all the available oxygen being used up. The pressures quoted further justify this explanation. As the curve starts from atmospheric pressure, we can find the percentage reduction in volume of any entrapped gas by dividing the maximum constant reduction by atmospheric pressure. Assuming atmospheric pressure to be 760 mm. and dividing the 156 mm. reduction by that figure, we obtain approximately 20 per cent. Ordinary air contains approximately 20 per cent oxygen.

Such oxidation is a very serious matter, as oil oxidized under such conditions is highly acidulous. We have been able to increase the acidity of a cable oil 120 per cent by exposing it for 2½ hr. to cathode rays in the presence of air. This acidity means increased dielectric loss as a certain result, and many undesirable chemical actions as probable results. The redeeming factor lies in the fact that modern U. S. cable as received from the factory contains less than 1 per cent gas by volume.

I completely disagree with the suggestions which the authors make in their fourth conclusion for curing the evils described in the first two.

In paragraph (a) they suggest the use of chemically stable compounds. Chemically stable compounds are desirable only for their ability to resist oxidation. The oil of a well built and well installed cable does not have to resist oxidation.

In paragraphs (b), (c), and (d), they suggest freely supplying air to prevent vacuum formation. Even oils of the paraffine series (the most chemically stable series) will oxidize in the presence of oxygen and a silent electric discharge. Everything known to me indicates that air must be kept out of cables, and not intentionally admitted as suggested.

In paragraph (e) they suggest that transformer oil be supplied under pressure at the joints. Sylphons filled with light oil at the joints of cable of the ordinary type will not prevent vacuum formation 20 ft. away under normal load change. They more thoroughly impregnate the immediately adjacent cable, driving the small percentage of cushioning gas normally present to the center of the length. Very high pressures and vacua result in the reimpregnated part. There may be objectionably large gas collections midway between sylphons.

**E. S. Lee:** When results are reported such as in this paper we are always interested in the quality of the cable insulation concerned as a basis for the applicability of the results. As Mr. Salter has shown, the samples from which these results were obtained were of what we should consider to be inferior cable. Extended application of the data reported is therefore not permitted. Since these are only preliminary results, more data will doubtless be forthcoming on samples of other quality.

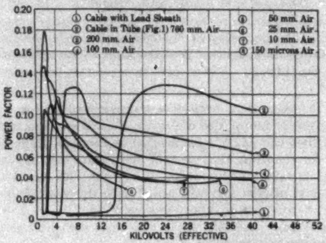

FIG. 3—VARIATION OF DIELECTRIC POWER FACTOR WITH VOLTAGE AT VALUES OF AIR PRESSURE BELOW ATMOSPHERIC

The study of the internal pressure existing throughout treated-paper insulation is most important and the authors have done well to put time upon it. Figs. 3 and 4 submitted herewith show in an exaggerated way the effect upon the power factor of air pressure of different values obtained during studies of this phenomenon. The results were obtained from treated-paper insulated cable with 9/32 in. of insulation.

Curve 1 shows the power-factor variation with voltage for the normal cable with the lead sheath in place. Curve 2 shows the result after the lead sheath was removed and a brass tube placed over the insulation with an annular air space 0.120 in. wide, making the volume of air equal to 0.68 that of the volume of the insulation. Curves 3 to 8 show the effect of reducing the air pressure. Curves 9 to 12 show the effect of increasing the air pressure. The attainment of a characteristic maximum of power factor is noted. The change in the power-factor characteristic is considerable and though exaggerated for good insulation, clearly shows the trend.

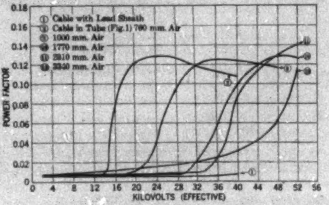

FIG. 4—VARIATION OF DIELECTRIC POWER FACTOR WITH VOLTAGE AT VALUES OF AIR PRESSURE ABOVE ATMOSPHERIC

These power-factor characteristics correlate well with life of the insulation in that pressures of internal air below atmospheric result in shorter life while pressures above atmospheric give longer life than at atmospheric pressure.

**R. J. Wiseman:** I have read with great interest the paper on cables and have tried to appreciate the data presented but without success. Seeking the cause of my lack of understanding of the results, as I do not believe such results can be obtained on most American cables in view of data which have been obtained on the latter, I have made the assumption for myself that the cables on which these tests were conducted did have many vacuous spaces and, therefore, the results should be interpreted in this light. I doubt if these cables are of as good quality as can be obtained here in America. It would be of interest to us if the authors would state what the percentage saturant to paper is for these cables. If the authors found that air was being propagated along the stranded conductor, then the conductor did not have any saturant in the strands as it should have.

The paper is of value as a warning as to the conditions existing in a cable if it is not sufficiently saturated and how short the life of a cable can become under such conditions. For example, let us refer to Fig. 5. In the first place, insufficient data are given to warrant plotting such a curve. The authors could easily plot a straight line and it would be equally as accurate. However, taking the curve as drawn, the life of the cable at atmospheric pressure and a voltage of 60 kv. is only 5 hr. A good cable of this design would last about 350 hr. at this voltage, which is only three times as high as the operating voltage. We are making tests today at 3.6 times operating voltage for 24 hr. and the cable must not fail or show signs of deterioration.

We do not get a clear picture of the influence of pressure and vacuum on a cable from any of the curves dealing with the life of a cable as the life is too short even for a cable under pressure.

The curve shown in Fig. 17 cannot be taken as the true life curve of a cable if based on Fig. 5.

I cannot agree with the statement given in the third paragraph under *Losses in Cables vs. Function of the Duration of Voltage Application*, that "This shows that the chief causes of the breakdown in the cable are chemical alterations, not pyroelectric effects." If chemical changes did take place, then the oil was a most unstable one. If the failures were examined, they would probably show severe burning of the paper from ionization caused by poor saturation. In this case, breakdown was a thermal or pyroelectric effect. Breakdown, in general, is due to the ionization of the insulation, paper and oil, which may or may not cause heat.

I suggest that the authors state in the titles to Figs. 19 and 20 that the tests were made at 60 kv.

The first three conclusions arrived at by the authors should be qualified, namely, "in poorly saturated cables." Under the fourth conclusion, I agree with "a," but "b," "c," and "d" do not sound feasible. Keep air away from a cable as far as possible. By using pressure and forcing the oil from the joint into the cable "e" really reduces the volume of the voids.

What is wanted is a cable free of all vacuous spaces; therefore, we ought to try to eliminate them. This is best accomplished by purchasing cable of high degree of saturation and then using pressure in the joints to force compound into the cable to correct for the deformations which may take place during installation. Also provide means for forcing the entrapped air out of the cable. This is done by using a higher pressure in every other joint. For example, if 10 lb. per sq. in. pressure is used in alternate joints, use 5 lb. per sq. in. pressure in the other joints. The advantage of a pressure-filled joint is obtained and at the same time the higher-pressure joints will cause the oil to move gradually along the whole cable to the lower-pressure joint and carry any air present along with it.

**W. A. Del Mar:** Mr. Salter gave a most interesting and admirable discussion. He started, however, with a hymn of praise of the life test which was adopted by the Russian experimenters. It is rather interesting to note that if the experimental data of the Russians are verified, it is possible to increase the life test of a cable in a way which will decrease its life in actual service. That is to say, by applying a vacuum of 5 cm. with a test voltage three times the working voltage, the life of the cable will be increased, whereas that same vacuum at working pressure would decrease the life of the cable. This suggests that there is nothing in this paper which supports the value of the life test but rather the contrary.

**T. F. Peterson:** (communicated after adjournment) Ordinarily I am not in sympathy with those who criticize honest attempts to get fundamental data because test conditions differ from those met in practise. In the case at hand, however, such broad conclusions and specific recommendations have been made that it may not be amiss to make certain comparisons.

The majority of the tests were made under vacua and indeed point to the superiority of one vacuum over another, (Figs. 6, 7, 8); still, conclusions concern themselves primarily with the use of internal pressure for improving cable operation. The imperviousness of impregnated paper to air passage is noted, yet no mention is made of difficulties which may be encountered in stabilizing the air pressure throughout the body of insulation for various temperatures of either the test sample or installed cable.

The seemingly peculiar "life-pressure" characteristics are due to the negatively sloping or drooping "power-factor—voltage" curve and the fact that these curves are shifted to the left as pressure is reduced. A maximum point in the "life-pressure" curve indicates that a line parallel to the $Y$ axis of Fig. 15, through the voltage of life test, will cut negatively sloping portions of power-factor curves for pressures in the range studied. These negative slopes indicate that all air is ionized. In practise we seek to operate with no air ionized, that is, at a point on the flat part of the power-factor curve. Obviously, increasing pressure of air increases (proportionally) the voltage at which ionization (upward bend in curve) takes place. Though pressure increase is desirable it does not follow that air ducts or the like are to be recommended. Due to imperviousness of paper, temperature changes may result in undesirable pressure conditions within the body of insulation, which may exist for the long period necessary for stabilization. A perfectly filled or impregnated cable with oil ducts is far superior.

The characteristics met with in this study are due in a large measure to the negatively sloping "power-factor-voltage" curve. I take exception to the author's statement that this is due to the fact that the loss in air after ionization is constant. The gradient is constant but current through gas as well as cosine of phase angle between gradient and current varies with voltage $E$ and so, while loss is not proportional to $E^2$, it is not constant.

A complete solution follows:

Let

$r_1$ be radius of conductor in mils
$R$ be radius of inside sheath

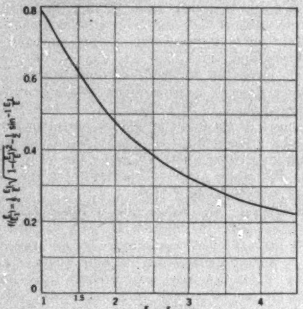

FIG. 5

$n$ the no. of air pockets per cu. mil of insulation
$v$ = volume of air pocket (all assumed the same size)
$g_1$ the gradient in air to break down film of thickness found

$$\frac{K_2}{K_1} = K = \text{ratio S. I. C. of paper to air} = 3.5$$

$$g_2 = \frac{g_1}{K} = \text{gradient in cable when air film breaks down}$$

$i$ the current density through insulation
$i_c$ the capacity current density through air film

Loss in solid insulation $= E^2\, C\, \omega \sin \psi_2$.
Loss/unit volume of air $= g_1\, i \sin \psi_1$

$$\sin \psi_1 = \frac{\sqrt{i^2 - i_c^2}}{i} \sqrt{1 - \frac{l_c^2}{l^2}}$$

$$= \sqrt{1 - \left(\frac{g_1\, K_1\, \omega}{g_2\, K_2\, \omega}\right)^2} = \sqrt{1 - \frac{g_1^2}{g_2^2\, K^2}}$$

At radius $r$ $\quad g_2 = \dfrac{E}{r \log \dfrac{R}{r_1}}$

Loss/unit volume of ionized air

$$= g_1\, i \sqrt{1 - \left(\frac{g_1}{\dfrac{E}{r \log \dfrac{R}{r_1}} K}\right)^2}$$

Total air loss =

$$\int_{r_1}^{r = \frac{E}{\frac{g_1}{K} \log \frac{R}{r_1}}} v\, n\, 2\, \pi\, r\, g_1 \frac{E\ C\ \omega}{2\, \pi\, r} \sqrt{1 - \left(\frac{g_1}{\dfrac{E}{r\ \log \dfrac{R}{r_1}} K}\right)^2}\, d\, r \qquad (1)$$

Let $\quad \dfrac{g_1 \log \dfrac{R}{r_1}}{K\, E} = c_1$

$$\text{Total air loss} = \frac{v\, n\, g_1\, E\, C\, \omega}{c_1}$$

$$\left[\frac{\pi}{4} - \frac{c_1\ r_1}{2} \sqrt{1 - (c_1\, r_1)^2} - \frac{1}{2} \sin^{-1} (c_1\, r_1)\right] \qquad (2)$$

$$c_1\, r_1 = \frac{g_1\, r_1}{K} \log \frac{R}{r_1} \times \frac{1}{E} = \frac{E_1}{E}$$

$E_1$ is voltage for breakdown of air at conductor.

$$\text{P. F.} = \frac{\text{Loss}}{E^2\ C\ \omega} = \frac{v\, n\, K}{\log \dfrac{R}{r_1}}$$

$$\left[\frac{\pi}{4} - \frac{1}{2} \frac{E_1}{E} \sqrt{1 - \left(\frac{1_1}{E}\right)^2} - \frac{1}{2} \sin^{-1} \frac{E_1}{E}\right]$$

$$f\left(\frac{E}{E_1}\right) = \frac{1}{2}\left[\frac{E_1}{E} \sqrt{1 - \left(\frac{E_1}{E}\right)^2} + \sin^{-1} \frac{E_1}{E}\right]$$

is plotted in Fig. 1. (3)

Expression (3) may be written

$$\text{P. F.} = \frac{v\, n\, K}{\log \dfrac{R}{r_1}}\left[\frac{\pi}{4} - f\left(\frac{E}{E_1}\right)\right]$$

$$= k_1\left[\frac{\pi}{4} - f\left(\frac{E}{E_1}\right)\right] \qquad (4)$$

Expression (4) is true until all air is ionized,

*i. e.*, until $\quad g_1 = \dfrac{E_2}{R \log \dfrac{R}{r_1}}$

Upper limit in (1) should then be $r = R$

When $E > E_2 \left(E_2 \text{ approx.} = \dfrac{R}{r_1}\right)$

$$\text{P. F.} = k_1\left[f\left(\frac{E}{E_2}\right) - f\left(\frac{E}{E_1}\right)\right] \qquad (5)$$

To this power factor must be added $\sin \psi_2$.

Curves from Fig. 10 of the paper by Dawes and Hoover and Fig. 16 of the present paper are replotted in Fig. 6. Knowing $E$, from the bend and one other point, $k$ may be computed. The points indicated are then determined using equations (4) and (5).

Since $\quad k_1 = \dfrac{v\, n\, K}{\log \dfrac{R}{r_1}}$

$$v\, n = \frac{K_1 \log \dfrac{R}{r_1}}{K} = \text{per cent air by volume}$$

= approximately 0.9 per cent for the cable used by Dawes and considerably greater for cable used by the present authors.

The agreement of computed points and curves is close except in the case of $A$. This should be reduced by the per cent increase in capacity due to breakdown of air. Capacities are directly proportional to voltages across paper.

Below ionization voltage

$E_2$ (across paper) $= E\, (1 - K\, n\, v)$

With breakdown over insulation to distance $r$

$$E_2' = E - g_1\, n\, v\, (r - r_1) - K\, n\, v\, E\, \frac{\log \dfrac{R}{r}}{\log \dfrac{R}{r_1}}$$

$$\frac{C}{C'} = \frac{E_1}{E_2'} = \frac{1 - K\, n\, v}{1 - \dfrac{g_1\, n\, v\, (r - r_1)}{E} - K\, \dfrac{n\, v \log \dfrac{R}{r}}{\log \dfrac{R}{r_1}}}$$

Due to action of space charge, etc., the capacity changes are undoubtedly greater than this relation would indicate.

**C. F. Hill:** (communicated after adjournment) The results of the paper seem to point to a rather definite deterioration of paper insulation under corona in air and a decrease in life with increase in vacuum. The curve of Fig. 5 indicates a change in cable life of about five times, over the range of pressures used, but it hardly seems justifiable to assume a second peak at about 50 mm. vacuum from the data given. It may be possible to explain this general falling off in cable life with decrease in pressure as due to the increase in energy located in the ionized space and the increase averaged energy of the ions as the mean free path increases, and a minimum of this effect would be expected near the pressure for which the mean free path becomes equal to the spacing between layers, although the decrease in number of ions would probably raise the critical pressure somewhat. The peak values of Fig. 6 and Fig. 7 are not to be explained so easily and it is difficult to find or explain any correlation with other data of the same paper, and especially with the variation of power loss or power factor with pressure. In Fig. 18 the values for power factor remain constant even though there is considerable change in pressure.

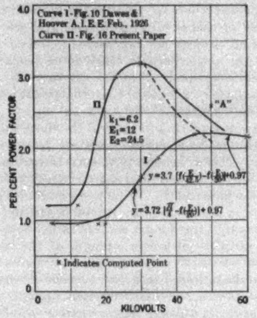

FIG. 6

The explanation given for the decrease in cable life with increase in vacuum is that there is a decrease in voltage drop across the air spaces with increased ionization and, of course, a corresponding increase in voltage stress on the paper. This also does not seem reasonable from the fact that the air spaces form a small part of the thickness and after the point of complete ionization the change in resistance of the air space becomes more or less negligible, so that the voltage on the paper does not change appreciably. The effect of the ionized gas in the paper seems a more logical cause for the deterioration.

The present paper coupled with that of Del Mar, read before the American Institute of Electrical Engineers in February, 1926, does, however, point out the dangers of corona in high-voltage laminated insulation, especially where considerable stress per mil is used and where the insulation is all organic. The problem exists in all laminated insulation but low working stresses have not made it so apparent. Where mica or other insulations can be included that withstand somewhat higher temperatures, the corona does no damage, even though the corona is more or less continuously present over long periods of time. In the case of cables, it would seem that we are justified in assuming that a well impregnated cable, if it remains so, should have a rather long life. But the effects of voltage on the oil alone will collect the absorbed or residual gases into pockets and coupled with the possibilities of gases seeping in during temperature cycles, it is difficult to keep a cable free from gas pockets.

If the formation of gas pockets proves to be the cause of cable failure, a possible method of detection of the condition of a cable would be to measure the variation of watt loss with voltage applied. The loss may be expressed in terms of voltage applied as

$$\text{Loss} = K\, E^n$$

For good solid insulation $n$ should remain equal to "2" over a considerable range of voltage, but if corona in gas pockets forms, $n$ should increase above the value "2", depending on the area of the gas pockets. The possibility of getting a sensitive method for such measurements remains a matter of experimental study.

The formation of gas pockets, and these becoming ionized, also suggests an explanation of the "tree-like" paths along the plane of the paper layers in that static charges may form around or just beyond the boundary of the pocket and discharge to the ionized space. Such discharges may have enough energy under several repetitions to burn paths in the paper layer and thus start faults such as have been noted in a number of cases of cables in service.

**W. N. Eddy:** (communicated after adjournment) The authors find that for each life-test voltage there is a certain optimum value of the internal or void pressure, the life decreasing as the pressure increases or decreases from this value. Their results as plotted in Fig. 8 indicate that at the operating voltage (considerably lower than their test voltage), the lowest internal pressure (c) would give the longest life and the highest pressure (a) the shortest life. This is of especial interest as it is believed contrary to general experience.

In explanation of their results, they suggest that with decreasing void pressure, the dielectric loss will increase because of the decreasing ionization voltage of the voids. This will continue until all of the internal air is ionized. "With a further increase of the internal vacuum the loss will decrease, the dielectric strength of air will decrease and, therefore, the voltage drop across the air will also decrease." The last part of this explanation is not easily acceptable. It is not seen how a decrease in the dielectric strength of air can cause a decrease in the voltage across an already ionized void.

Comparison of the authors' Fig. 8 with the life-test results published in 1926 by Mr. F. M. Farmer[1] brings several pertinent indications.

1. In comparison with the variation between separate tests found by Mr. Farmer, the influence of internal pressure on the author's tests appears quite small.
2. While the slope of the authors' curves seems to increase with the internal pressure, at 200 mm. vacuum (50 cm. pressure abs.) it is the same as the average of Mr. Farmer's tests.
3. The life of the cable used by the authors is materially below what is believed to represent acceptable insulation quality.

Because of the incomplete pressure distribution throughout impregnated paper insulation if the impregnating compound is not liquid, it is suggested that each pressure given by the authors may represent that of only a small portion of the total void space in the cable. This would explain the relatively slight influence of the pressure on the life.

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[1] F. M. Farmer, A. I. E. E. TRANSACTIONS, 1926, Vol. XLV, *Tests of Paper Insulated Cables*.

In general, the authors' test results are of considerable interest. Because of this, it is hoped that they will continue their investigation and that tests on cable of higher insulation quality through a wider range of test voltages will be included therein.

**F. M. Clark:** (communicated after adjournment) This paper must be considered as a preliminary report of research investigations which have not yet been completed. Because of this, there are, no doubt, many conclusions with which one might be tempted to disagree and which probably the authors themselves may find untenable as the result of later researches. This paper, moreover, must be considered in connection with previous articles on the same subject of vacua in cables and the resulting dangers inherent with this condition.

If it does nothing more, this paper will be of value in again attracting attention to the problem of cable stability under long-time service conditions. Unfortunately it is still in some instances the practise to consider a treating compound merely as something which acts to prevent water absorption as well as to obtain the elimination of air from the dielectric. Work at Pittsfield serves to emphasize the fact that grave danger may accompany the use of a treating compound which does not possess certain specific physical and chemical characteristics. Physical characteristics in themselves appear to be of extreme importance.

The factors which influence void formation in the treated dielectric are:

1. Chemical changes in the residual gases under the influence of ionization.
2. Thermal expansion and contraction of the treating compound, and
3. Gas solubility in the treated compound.

The last of these problems has not received the attention which may be warranted by its importance. From experiments which we have carried out we have found clear evidence that the solubility of certain gases in petroleum products increases with the temperature. This may serve to explain the changes in pressure described in Fig. 18 of the paper. Presumably in cable structure we should avoid the presence of such gases. If we have present only those materials whose solubility in the treating compound decreases with increased temperature, gas areas of low pressure would be invariably absent.

The second factor involved in void formation, that is, the expansion and contraction of the compound, is a problem which appears to be difficult of solution in view of the fact that most materials available for treating purposes possess about the same thermal coefficient of expansion. However, even here I believe that considerable improvement over the present materials in common use can be made.

The problem of chemical changes in the residual gases under ionization has been described by a variety of research workers. There seems to be clear evidence that the formation of wax in cables under stress is accompanied by a gassing condition with the eventual formation of dry low-pressure gas areas.

In the conclusions drawn by the authors it is pointed out that the dangerous effect of internal vacua demands the use of chemically stable compounds. From experience in investigating this problem I should like to add that the compound should be chemically stable when no voids or gas pockets are present. To hope to obtain a compound stable to voltage in the presence of ionizing effects which accompany the application of voltage on low-pressure gas areas appears to be a hope without foundation. We have carried out a considerable number of experiments in Pittsfield and in every case we have been able to disintegrate compound-treated paper or untreated paper in the presence of air or other gases such as hydrogen. Although there are some apparent variations in the ease with which certain impregnating materials are waxed, nevertheless I believe that these variations are not important from the practical standpoint and that they may be very largely explained by irregularities in the testing methods.

The authors have found that increased life accompanies increased pressure applied to the cable. In Pittsfield we have carried out similar experiments and have found that with untreated paper the power factor invariably increases with the gas pressure applied. We have about concluded that this increased power factor is a function of the moisture content of the gas under pressure. I wonder if the dangers from moisture contamination have been eliminated in the work described in this paper. We have also found that early failure in capacitors under voltage at high pressures has invariably been due to a change in the applied gas pressure. Any change leading to a diminished pressure will, of course, tend to remove the gas dissolved in the treating compound with the resulting formation of gas pockets. This is a factor which must be considered in work of this type and is very difficult to overcome since it is almost impossible to maintain pressures with a high degree of accuracy over long periods of time.

The authors have presented a number of interesting charts showing the relationship existing between pressure applied and resulting life and power factor. It will be of considerable importance to learn how well subsequent research work serves to check the data presented. The explanation given in the paper appeared to me, at first, to be untenable. In Fig. 18 is illustrated the change in vacuum and power factor as a result of prolonged life test. It appears to me that this increase in vacuum is what would be expected when air pockets are placed under voltage. The formation of ozone, nitrogen oxides, and the oxidation of the oil would all tend to produce such an effect. It would be interesting if the authors would carry out a similar experiment in the absence of air using hydrogen gas instead. Under such conditions it appears probable that the pressures, instead of decreasing, would increase.

The authors suggest that in general the dielectric strength of the solid insulation may depend upon the pressure of the surrounding air. This I believe is a very important suggestion which ties in very well with the research results which have been obtained in our laboratory. In fact, we have about concluded that the ordinary tests which are run on liquid and solid dielectrics are invariably a test for gas content rather than a test which involves the ultimate dielectric strength of the liquid or solid material.

The authors have found that the decrease in temperature 25 deg. cent. results in an increased internal vacuum to about 180 mm. of mercury. It appears that a number of influences must be at work to cause such a decrease in pressure. For example, I do not know the type of compound which was used in this cable but it is safe to assume that for a 25 deg. cent. change in temperature the expansion of the compound did not amount to more than 2 per cent by volume which would result in not more than 20 or 25 mm. of mercury change in pressure.

The power factor temperature curve of Fig. 19 is used as an argument in favor of the rejection of the pyroelectric theory of insulation failure. It is stated that a continual rise in temperature in the cable should result if the pyroelectric effect were of importance. I do not believe that the relation such as that shown in Fig. 19 is of considerable importance from the standpoint of the pyroelectric theory. While this theory has been, and probably still must be, modified considerably from its original form, it still appears to offer considerable promise in the explanation of those dielectric failures which are not caused by secondary effects such as chemical change in the dielectric resulting in gas formation, etc.

I want to call to the attention of the authors that the relationship between temperature and power factor is a distinct function of the experimental conditions. It is true as indicated in the paper, that the V-shape relation between power factor and temperature does exist with a minimum at about 40 deg. cent. This appears to be irrespective of the type of impregnating materials under test. But I want to call attention especially to the fact that the minimum point in this V-shaped relation can be changed at will. In our work we have been able to shift it from 40 deg. cent. to temperatures below room temperature. We have also been practically able to eliminate the high temperature side of the V so that the power factor drops to a value which is maintained almost constant from 30 or 40 deg. cent. up to 70 or 80 deg. cent. It appears probable from our work that two different types of phenomena are brought into play when the temperature is raised on an insulation during power-factor tests. With temperatures just above room temperature the predominating factor involved has a negative temperature coefficient. With temperatures normally above 40 deg. cent. the influence involved has a positive temperature coefficient and it is this factor which is primarily concerned in normal breakdown and with which the pyroelectric theory chiefly deals.

The authors conclude, among other things, that it may be desirable to pump dry air through ducts in the core of the cable to maintain pressure higher than that of the atmosphere. This would, of course, bring about a desirable condition from the standpoint of pressure but at the same time it must be remembered that by supplying air under pressure we are increasing the amount of gas actually dissolved in the treated dielectric. Any drop in pressure, therefore, would result in the elimination of this dissolved gas and the formation of gas pockets. I firmly believe that the most dangerous single factor which could be applied to a cable under service conditions would be the pumping of air under pressure. It appears that the most likely way of maintaining high pressure inside of a treated dielectric would be the application of a hydrostatic oil head.

**Alexander Smouroff:** In view of the interest shown in more detailed characteristics of the cable used during the investigation, I am first giving some further information about that cable.

The ratio of compound to impregnated paper, by weight, is 45 per cent. The compound contains 50 per cent of resin and 50 per cent of naphtha-base oil having a viscosity 6 deg. Engler at a temperature 50 deg. cent. The paper used in the cable has the following characteristics:

thickness $s = 0.2$ mm.
specific density 0.7
breakdown gradient for 1 sheet 35 to 48 kv. per mm.
breakdown gradient for 2 sheets 43.2 kv. per mm.
breakdown gradient for 3 sheets 37.3 kv. per mm.
$Q = 500$ to 350 cu. cm.
$A = (0.25 \text{ to } 0.35) \times 10^{10}$

where $Q$ is the volume of air that passed through a sample of paper having a surface $S = 10$ sq. cm. during a lapse of time $t = 60$ seconds at a pressure $h = 100$ mm. water, and $A$ is the constant of Emanueli[2] from the formula $Q = \frac{I}{A\,\eta} \cdot \frac{S}{s} \cdot h\,t.$

where $\eta = 0.0001808$ is the viscosity of air.

The low quality of the cable can be chiefly explained by the unsuitable properties of the paper used and perhaps partially by an insufficient cooling of the cable before the lead sheath was put on, which certainly contributed greatly to the formation of voids or air spaces in the cable during the cooling of the sheath. Indeed another cable prepared afterwards in which another kind of paper was used, had quite different properties.

The characteristics of that paper were the following:

Thickness $s = 0.19$ mm. (⅓ of the cable's thickness)
specific density 0.72
breakdown gradient for 1 sheet 55.6 kv. per mm.
breakdown gradient for 2 sheets 52 kv. per mm.
breakdown gradient for 3 sheets 55 kv. per mm.
$Q = 20$ cm.$^3$
$A = 6 \times 10^{10}$
Thickness $s = 0.12$ ($^2/_3$ of the cable's thickness)
specific density 0.72
breakdown gradient for 1 sheet 60.7 kv. per mm.
breakdown gradient for 2 sheets 62.5 kv. per mm.
breakdown gradient for 3 sheets 61.5 kv. per mm.
$Q = 22$ cu. cm.
$A = 8.2 \times 10^{10}$

The ratio of compound with 40 per cent resin to impregnated paper, by weight, for that cable was about 40 per cent. For the same thickness of insulation, 10 mm., the life of the cable was 50 hr. for a voltage of 100 kv. and 1 hr. for a voltage of 140 kv. The tangent of the loss angle did not change its value till the voltage of 80 kv. was reached and was always less than 0.02. Thus the properties of this cable approached the properties of cables of American make, as they were given by Mr. Salter.

Mr. Del Mar's explanation of the process of feeding cables with oil is very interesting indeed. But it is necessary to note that cables with a loose paper winding can be advantageously used only with oil feeding. I believe that normally cables must be wound as tight as possible for in that way the volume of compound is diminished, which results in the decrease of air content in the cable. The European practise is based on the belief that it is possible to manufacture cables up to the voltage of 66 kv. in such a way that the cables shall operate without oil feeding.

Mr. Del Mar explains the difference of oil and paper weights for one European cable as caused by a loose paper winding. I believe that that difference may be explained rather by the difference in the densities of the papers used in American and European practise, *i. e.*, by a greater porosity of the paper.

In reply to Mr. Connell I must state that the propagation of pressure along the cable took place along the core and the surface of the latter. The pressures in the interior of the insulation could differ from the air pressure in the core, for, as experiment showed, the radial propagation of pressure did not take place. Oil as it is pumped in the cable passes quite freely through the core of the latter forming a jet at the opposite end of the cable. Tests were made by pumping oil into the cable out of a filter-press under a pressure up to 6 atmospheres.

Although Mr. Connell's suggestion that the formation of vacuum during the experiments could be explained by a complete using up of the available oxygen for oxidation of the compound, is supported by numerical data, nevertheless I believe that such a complete oxidation is hardly possible, inasmuch as recent researches,[3] in which Mr. Connell took part, suggest that the disintegration of compounds under the influence of ionization is accompanied by liberation of hydrogen and polymerization and condensation of the particles of the compound. Even if we grant that such changes in structure of the molecules of the compound are not accompanied by change of volume of the compound, the liberated hydrogen will increase the volume of the gas although a part of the oxygen would be used up in oxidation of the compound.

By chemically stable compounds I meant such compounds as would better withstand the influence of ionization, which must depend upon the chemical structure of the compound.

In clauses *b*, *c*, and *d* of paragraph 4 of the conclusion I meant only that the cable, which was submitted to experiments, would have a longer life if the pressure of air was raised to such a value that ionization of air with all its bad consequences would not take place. However, in practise it is much better to fill a cable with oil, as suggested in clause *e* of the conclusion, for in that way the danger from ionization and oxidation is noticeably reduced. The experiment showed that by filling with oil under vacuum, the tested cables increased their life 7.5 times in comparison with their life without this extra oil under a vacuum of 300 mm. as such a cable could resist during 15 hr. a tension of 60 kv. when the cable was filled with oil.

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[2] "Compte Rendu des travaux de la troisième session de la Conférence Internationale des Grands Reseaux Electriques à Haute Tension," Paris, 1925—L. Emanueli, "Une ligne experimentale en cable fonctionnant à 130,000 volts," T. I., p. 1147.

[3] C. F. Hirshfeld, A. A. Meyer, and L. H. Connell, "Mechanism of Cable Failure," *Electrical World*, November 12, 1927.

In reply to Mr. Eddy's observation I would state that each experiment corresponded to a constant tension and also to a constant air pressure with a variable quantity of air in the core of the cable and around it, as the pressure was maintained constant during the whole duration of each experiment. In view of this fact, a given tension with increase of vacuum on a new cable sample made ionization take place at a lower gradient in air, which resulted in a higher tension on the solid insulation.

The volume of voids in the cable was measured directly by means of pumping oil in the cable and by means of connecting the cable under atmospheric pressure with its other end well sealed to a vessel of known volume and containing air under a known vacuum. The volume of voids measured by both methods proved to be about 30 cu. cm. per m. or 3.7 per cent of the volume of insulation. This volume corresponds to the space between the conductors of the core as it was checked by calculation. This shows that in the cable there was a very little quantity of compound in the core. Supplementary tests made after the paper was written show that the character of the curves in Figs. 5 to 7 holds for all pressures and voltages, as may be seen from the curves in the accompanying Fig. 7.

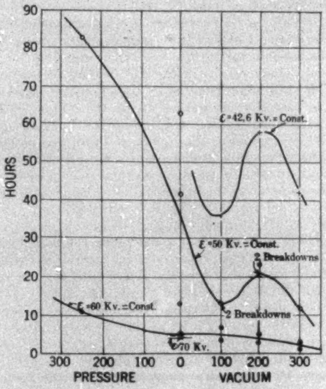

FIG. 7

As regards the possibility of changes in the parasitic volumes of air in the rubber tubes to the manometer, it must be noticed that the rubber tubes were of a special rigid type with thick walls and a small diameter so that their interior volume could not appreciably change under the comparatively small pressure variations during the experiments. The connection of the manometer to the end of the cable was made by means of a rubber tube that was put on the cable insulation and on a brass cone, which allowed the use of a rubber tube of a small inner diameter. Within the cone was soldered a wire, connected to the core of the cable, from which the insulation was taken off on a length of 10 mm. The cone together with the upper electrode was connected to the high-tension winding of the transformer. This arrangement (1) allowed an easy control of the vacuum under voltage, (2) secured the normal state of compound on the cable ends, and (3) kept away all possibility of ionization of air outside of the cable, for the brass cone acted as a screen on the wire connection to the core of the cable and on the air in the interior of the cone at the ends of the cable.

I wholly agree with Mr. Clark, that the increased solubility of gases in compounds with rising temperature is probably one of the causes of the vacua, as shown in Fig. 18.

Indirectly it could be seen from accelerated life test experiments made with cables previously heated five times during 5 min., each time with an electric current of about 800 amperes under atmospheric pressure. Between successive heatings the cables were allowed to cool during 5 min. These experiments showed a noticeable reduction of cable life. A cable submitted to such a treatment could withstand a tension of 60 kv. during 37 min. only and another a tension of 50 kv. during 42 hr., 22 min.

I am in thorough accord with Mr. Clark's statement that moisture increases the loss in paper. I have already pointed out in my paper on the "Physical Nature of Dielectric Phenomena," reported before the fourth International High-Tension Conference in Paris[4], that moisture could act as a catalyst in the electric breakdown of an insulator, for the presence of moisture must decrease the ionization potential.

I certainly agree that it would be very interesting to make an accelerated life test with a cable filled with hydrogen to avoid the possibility of oxidation.

Mr. Clark is quite right in pointing out the danger in pumping air into a cable under pressure in cases when this pressure for some reason would be lost.

I wholly agree with Mr. Peterson that in practise cables must not be filled with air although I had in view only the results directly connected with the tested samples of cables. I cannot agree with Mr. Peterson's solution for the power factor with consideration of ionization of gas films, for this solution is not quite clear to me. I cannot see whether Mr. Peterson represents the air in a cable in the form of thin concentric air films or in the form of uniformly distributed air bubbles shunting the solid insulation. If the gradient in air to break down a film thickness found is $g_1$ and it is assumed that $g_2/g_1 = k =$ constant, we shall always have from the formula given by Mr. Peterson sin $\psi_1 = 0$. I believe that this power factor could be obtained in another way by assuming an in-phase ionization current in air and a leading displacement current with a conduction current in the solid insulation.

Mr. Dawes' observation of the necessity of shielding Schering's bridge and of bringing suitable points of the bridge and shielding to the same potential in order to avoid errors is quite true, but this observation holds chiefly for small capacities measured and for small loss angles, which was not the case during the experiments performed.

The assumption that the loss $P_1$ in air remains constant after complete ionization is certainly only a first rough approximation. With an increase of current through the air under increase of voltage through the insulation there will be a variation of loss in the air. With an increase of current the voltage through the air will decrease, as always happens for ionic conduction, for instance in an electric arc, and thus the voltage through the solid insulation will increase.

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[4] "Compte Rendu de la Quatrième Conférence Internationale des Grands Reseaux Electriques à Haute Tension," Paris, 1927. A. Smouroff, Sur les caractères physiques des phénomènes diélectriques.

# Hot Cathode Neon Arcs

BY CLIFTON G. FOUND[1] and J. D. FORNEY[1]
Non-member Non-member

### Mechanism of Light Production in a Gas

THE present picture of an atom is one of a positively charged nucleus surrounded by electrons which have a definite arrangement in the normal atom. When the atomic system receives energy, it does so in a restricted manner. It cannot absorb energy continuously but only in discreet amounts which are integral multiples of a certain constant known as the quantum constant. The absorbed energy is utilized in changing the configuration of the electrons in the atom. An electron is moved farther from the nucleus to a position of higher energy content. Thus, we see that an atomic system contains a series of energy levels for the electrons. When an electron moves from an energy level, $E_2$, to a lower level, $E_1$, the difference is emitted in the form of monochromatic radiation, the frequency of which is determined by the relation

$$E_2 - E_1 = h \nu,$$

where $\nu$ is the frequency of radiation and $h$ is the quantum constant. Every type of atom has a different series of energy levels, and consequently the radiation emitted by an excited atom is characteristic of that particular type of atom. Also, from the restricted nature of the energy changes, the radiation will consist of radiations of definite frequencies which will appear as a series of lines in the spectrum.

One method of transferring energy to a gas atom is by electron bombardment. An electron traveling under the influence of an electric field has an energy $V e$, where $V$ is the voltage drop through which the electron has passed, and $e$, the charge on the electron. If, now, the electron collides with a gas atom, part or all of the energy of the electron will be transferred to the atom, providing the restricted quantum condition is fulfilled, namely,

$$V e \geq h \nu$$

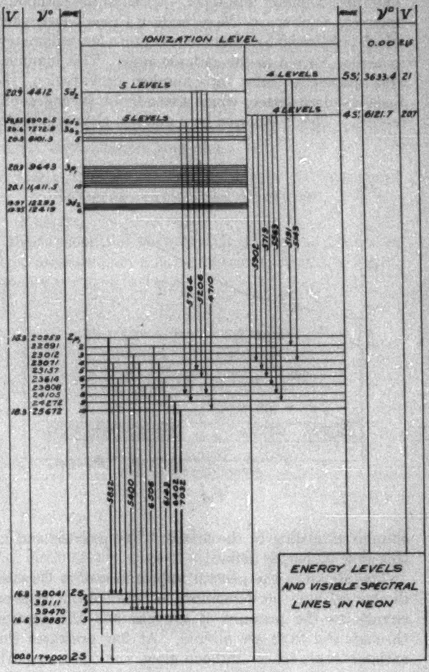
Therefore, we may speak of energy levels in terms of voltage equivalents. For visible radiation, $V$ has a value from 1.8 volts for the red to three volts for the violet.

A diagram for the energy levels for neon is given in Fig. 1.

It will be noted that the lowest level for neon corresponds to a voltage of 16.6 volts, which in emission is a line in the extreme ultra violet. It will be noted, also, that the level differences above this correspond to a voltage of about two volts and that the emitted radiation lies between 5800 and 7000 $A°\ U$. That is, in neon, the arrangement of the energy levels is such that practically all of the visible radiation is in the orange and red.

### Early Work on Gaseous Discharge Lights

Although the first artificial electric light was due to a gaseous discharge, we have become so accustomed to the incandescent type of lamp that we consider a gaseous discharge light as a very recent development. About 1850 Geissler first obtained light from tubes containing rarefied gases when he operated them in connection with an induction coil. In 1893 D. McFarlane Moore started his researches on the production of light from gaseous discharges. The first commercial installation of tube lights was made in Newark in 1904 and consisted of a tube 180 ft. long operated from a high-voltage transformer. However, the commercial development of gaseous discharge lights subsided with the development of the simpler tungsten filament lamp.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20.6 7272.8 3s₂
20.5 8101.3 5
20.3 9643 3p₁
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39111 3
39470 4
16.6 39887 5
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ENERGY LEVELS AND VISIBLE SPECTRAL LINES IN NEON

Fig. 1

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[1] Research Lab., General Electric Co., Schenectady, N. Y.

*To be presented at the Joint Meeting of the New York Sections of the A. I. E. E. and the I. E. S., May 18, 1928.*

### CHARACTERISTICS OF A GEISSLER DISCHARGE

A consideration of the characteristics of a Geissler discharge may permit a better understanding of the difficulties encountered in the early types of tubes and of the advantages of the hot cathode. One type of Geissler discharge may take place in an elongated tube with metallic electrodes at each end. When a high voltage is applied between the plates, a discharge takes place in the tube, which has the appearance shown at the bottom of Fig. 2. This is for nitrogen at a pressure of 0.5 mm. of mercury and a current of 5 milliamperes. The tube diameter was 6 cm. Close to the cathode is a narrow, dark space, the cathode or Crook's dark space, which is followed by a luminous region a few millimeters in width, known as the cathode glow. This luminous area gradually fades into another dark region, the Faraday dark space, which extends for several centimeters. This is followed by a uniform glow or positive column extending to the anode. The cathode end of this glow is sharply defined.

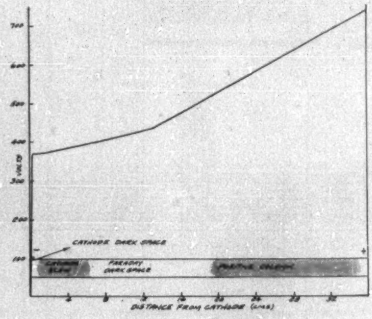

FIG. 2

The above is the general appearance of a Geissler discharge, but the dimensions of the various regions change as the pressure of the gas and the current through the tube are altered. At low pressures the cathode dark space, cathode glow, and Faraday dark space extend a considerable distance from the cathode. As the pressure is increased, all these regions diminish in length and the major portion of the discharge is made up of luminous positive column.

Using the method of the exploring electrode as developed by Langmuir and Mott-Smith,[2] the first named author has measured the potential distribution in a Geissler discharge. The results for the discharge in nitrogen, mentioned above, are shown in the curve of Fig. 2. It shows the existence of a high-voltage drop at the cathode. There is also a slight gradient in the Faraday dark space which, however, may be zero or even negative as shown by Compton, Turner, and McCurdy[3] in the case of mercury. Throughout the positive column the voltage increases uniformly to the anode. The drop at the anode may be positive, zero, or negative, depending on the dimensions of the anode and the current density. However, it is always small and of the order of only a few volts. The characteristic which imposes the greatest limitations on a lamp of the Geissler discharge type is the high voltage drop at the cathode. In the above case, this is 50 per cent of the total drop in the tube and is of the order of hundreds of volts. At higher current densities the cathode drop increases and may reach over a thousand volts. On account of the important part the cathode drop plays in these discharges, we shall consider it more fully.

### THEORY OF THE CATHODE DROP

As pointed out earlier in this paper, we must have electrons present in order to excite the gas atoms. Although we know very little concerning the origin of the primary electrons which cause ionization, it is generally believed that the discharge is maintained by the emission of electrons from the cathode which multiply by ionization by collisions. The exact mechanism of the process of the emission of these electrons is not known, but it doubtless is a result of bombardment of the cathode by positive ions. K. T. Compton and P. M. Morse[4] have developed a theory of the cathode fall in a Geissler discharge which is based on this process and which fits satisfactorily the present experimental evidence and also satisfies the known empirical relations. According to this theory practically all the current at the surface of the cathode is carried by positive ions.

In a tube with cold cathode, the positive ions strike the cathode with a high velocity due to the high cathode drop, and cause a mechanical disintegration of the cathode. This cathodic sputtering causes a blackening of the tube walls. Another result of the high cathode drop is a clean-up of the gas, causing the "resistance" of the tube to increase as the tube is operated. Also, there is a large consumption of energy at the cathode which yields no light and greatly decreases the efficiency. To avoid this large energy loss and consequent heating effect, and in order to decrease the amount of sputtering, the current density at the cathode of a Geissler tube has usually been chosen at about 10 milliamperes per sq. cm.

Thus, we may summarize the effects of the high cathode drop as follows:

1. It is impossible to construct a low-voltage tube.
2. In order to have good light efficiency, it is

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[2] Langmuir, *G. E. Review*, Nov. 1923. Langmuir and Mott-Smith, *Phys. Rev.*, 28, Oct. 1926.

[3] Compton, Turner, and McCurdy, *Phys. Rev.*, 24,659, Dec. 1924.

[4] K. T. Compton and P. M. Morse, *Phys. Rev.*, 30, 305, Sept. 1927.

necessary to make long tubes in which the ratio of cathode drop to total voltage is decreased.

3. There is a "clean-up" or disappearance of the gas. This may occur from other causes also, but is certainly increased due to the high cathode drop.

4. Blackening of the tube is caused by cathodic sputtering and in order to keep this low, there is a limit to the current density at the electrodes.

### Effect of Using Hot Cathode

What is the effect of replacing the cold cathode by a heated one capable of emitting electrons in sufficient numbers to supply the current through the tube?

There is no longer any necessity for the high voltage drop at the cathode as we already have plenty of primary electrons. All that is needed is a voltage sufficient to cause ionization of the gas. This voltage is never greater than 25 volts. Thus, the substitution of a hot cathode reduces the cathode drop to a few volts and we avoid all the difficulties caused by the high cathode fall in a cold cathode discharge. In other words, the replacement of the cold electrode by a hot electron-emitting one causes the discharge to pass from a glow to an arc, as defined by K. T. Compton.[5] His definition states: "An arc is a discharge of electricity between electrodes in a gas or vapor which has a negative or practically zero volt-ampere characteristic and a voltage drop at the cathode of the order of the minimum ionizing or minimum exciting potential of the gas or vapor." By an adjustment of the pressure, the region of cathode glow and Faraday dark space can be greatly reduced, so that the main portion of the tube is filled with the luminous positive column.

### Construction of Hot Cathode Arcs

In the previous paper, Dr. Hull has described the construction of a cathode capable of supplying very large currents. This type of cathode has been used in the construction of the neon tubes to be described in the remainder of the paper. A further description of this cathode seems unnecessary. The radiation type of cathode has a decided advantage over a filamentary cathode in the fact that large areas can be obtained without using excessive heating currents, as in the case of heavy filaments, and also without having a large voltage drop between the terminals as in the case of a long filament. In the latter case, if the voltage across the filament is much greater than the ionization voltage of the gas used, an arc is formed across the leads and the filament is burned out.

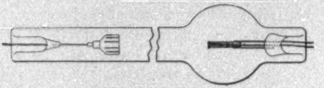

Fig. 3

The construction of a hot cathode neon tube is shown in Fig. 3. It consists of an elongated tube on one end of which is a cathode of the type mentioned, which is capable of giving an electron current of about 3.5 amperes when the heater is taking 60 watts. At the opposite end is an iron electrode which serves as anode. The pressure of neon in the tube is about 2 mm. of mercury. At this pressure practically all of the tube is filled with positive column.

### Electrical Characteristics of Discharge

Before mentioning the characteristics of the tube as a unit, we should like to discuss some characteristics of the discharge within the tube. Using the exploring electrode method, measurements of the potential distribution in a hot cathode neon tube show a cathode drop of about 25 volts followed by a uniform gradient throughout the tube. The drop at the anode varies from a few volts positive to a few volts negative, but is never very different from zero.

### Potential Gradient as a Function of Pressure, Current, and Tube Diameter

*1. Pressure.*

Measurements of the potential gradient as a function of the pressure show a flat minimum at from 2 to 5 mm. pressure as shown in Table I.

TABLE I

Discharge current = 2.0 amperes

| Pressure | Gradient |
|---|---|
| 0.2 mm. | 1.95 volts/cm. |
| 0.6 | 1.90 |
| 1.5 | 1.72 |
| 2.3 | 1.65 |
| 3.1 | 1.65 |
| 4.25 | 1.61 |
| 4.9 | 1.80 |

*2. Discharge Current.*

The voltage-current relation in the main portion of the discharge is shown in Table II. The voltage gradient decreases as the current increases, giving a negative "resistance" to the discharge.

TABLE II

Pressure = 0.2 mm. mercury

| Current | Gradient |
|---|---|
| 0.5 amps. | 2.1 volts/cm. |
| 1.0 | 2.0 |
| 2.0 | 1.95 |
| 3.8 | 1.87 |
| 6.8 | 1.78 |

*3. Tube Diameter.*

Table III shows the relation between tube diameter and potential gradient.

TABLE III

| | | | |
|---|---|---|---|
| Tube diameter.......... | 1.28 cm. | 1.95 cm. | 2.55 cm. |
| Gradient.............. | 3.36 volts/cm. | 2.15 volts/cm. | 1.75 volts/cm. |
| Product............... | 4.20 | 4.17 | 4.45 |

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[5] K. T. Compton, A. I. E. E. Trans., Vol. XLVI, 1927, p. 868.

This result is in accord with the theory of Shottky[6] who has deduced from theoretical considerations on the rates of diffusion of ions and electrons to the walls that the voltage gradient should vary inversely as the tube diameter. Results of Claude[7] on tubes filled with neon at a pressure of 2 mm. also give results in agreement with Shottky's equation.

### OPERATING CHARACTERISTICS

The over-all voltage-current relation for a tube 125 cm. long and 2.2 cm. diameter is shown in Fig. 4. On account of the negative "resistance" characteristic of the tube, the latter is inherently unstable and requires a resistance in series for stable operation. The value of this resistance must be greater than the resistance corresponding to the slope of the volt-ampere curve or the tube will not operate. It will be noted that for low currents, much greater series resistance is required, and also the change in slope is greater at low current values. Therefore, for most stable operation, it is desirable to operate at a current where the change in slope is least, as at this point a larger proportion of the available voltage can be utilized in the tube. Also, an inductance in series with the arc eliminates transients and permits steadier operation.

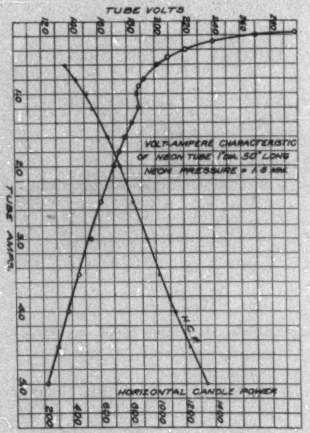

FIG. 4

### STARTING OF TUBES

On a tube in which the distance from the walls to the cathode is small compared to that between electrodes, the walls of the tube become negatively charged and it is necessary to remove this charge before a discharge will pass. This is true in the present tubes and there are three methods by which the tubes may be started.

1. A high-frequency discharge may be brought close to the tube.

2. An auxiliary anode may be placed close enough to the cathode for a discharge to take place to it. This produces ionization in the tube, which neutralizes the charge on the walls and by connecting the auxiliary and main anodes together through a suitable resistance the discharge can be transferred to the main anode.

3. By suddenly stopping the current in an inductance in series with the discharge, a high inductive kick, which causes enough ionization in the gas to allow current to pass, is produced in the main circuit. This type of starting device is used in the Cooper-Hewitt mercury vapor lamps and is the method we have employed for the tubes we will describe below.

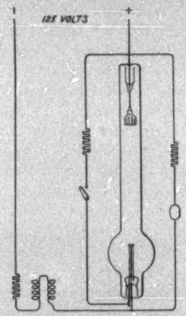

FIG. 5

### TYPES OF TUBES

1. *D-c. Tubes.* The circuit for a d-c. tube with stabilizing resistance and series inductance is shown in Fig. 5. In this tube the heater wire is so chosen that it requires the same current as the discharge. After the cathode is heated by means of the auxiliary circuit, the latter is opened and the discharge, which has been started by an inductive kick as described in the third method of starting, passes through the heater which now takes the place of part of the stabilizing resistance. This is a decided improvement over a Geissler discharge form of tube since the latter can be operated on a d-c. source of voltage only by using a special high voltage generator. A hot cathode tube of this type 2.2 cm. in diameter and 75 cm. long can be operated from a 125-volt d-c. line.

When both a-c. and d-c. voltages are available, the heater unit may be operated from the a-c. supply, while the arc itself may be run on direct current. The d-c. circuit for this tube, including the circuit for the method of starting by the inductive kick, is shown in

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[6] Shottky, *Phys. Zeit.*, XXV, 342, 635 (1924).

[7] Claude, *Comptes Rendus*, p. 479, 158 (1914).

Fig. 6. When the voltage is applied the tube is shunted by a mercury switch and a resistance which limits the current in this circuit to about one ampere. As soon as this current energizes the inductance the magnetic field from the coil tips the switch, breaking the auxiliary circuit very quickly (in less than 1/5000 of a second). This gives an inductive kick of about 2000 volts across the tubes.

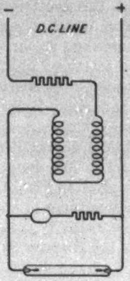

Fig. 6

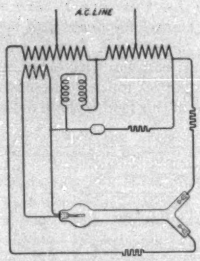

Fig. 7

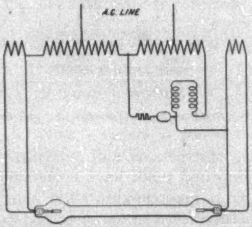

Fig. 8

2. *A-c. Tubes.* An a-c. tube is made with an anode in each of two short arms at the opposite end of the tube to the cathode. This tube, with its electrical connections, is shown in Fig. 7. The cathode is connected to the midpoint of an auto-transformer through a reactance. Each terminal of the transformer is connected through a small resistance to an anode. This arrangement permits a uni-direction current to pass through the tube. The reactance causes a lag in the current so that the two half waves overlap. This reduces the current to almost a constant value and there is no visible flicker in the lamp.

Another type of a-c. tube with connections is shown in Fig. 8. A hot electrode is placed at either end of the tube and operates as cathode on one-half cycle and anode on the other. A large reactance in series with the tube is necessary to eliminate flicker.

## LUMINOUS CHARACTERISTICS

Photometric measurements of a neon lamp show that as a first approximation the luminosity varies as the $^2/_3$ power of the current but owing to the negative volt-ampere characteristic, the light emitted is practically proportional to the watts at higher currents, as shown in Fig. 9. These measurements apply to the positive column only. Measurements of entire tubes show an over-all efficiency of 12 to 15 lumens per watt for d-c. tubes and 10 to 12 lumens per watt for a-c., which is about the same as the 100-watt size Mazda C lamp.

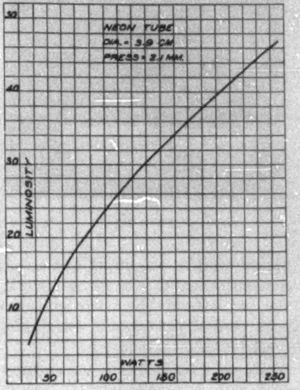

Fig. 9

A 220-volt tube, which is 2.2 cm. in diameter and 125 cm. long, operating at three amperes, has a luminous output of about 10,000 lumens.

## LIFE

Tubes have been operated on life tests and many have run over 3500 hr. At the end of this period there was practically no discoloration of the walls and no measurable change in the volt-ampere characteristics of the tube. Also, from the general appearance of the electrodes it does not appear too optimistic to predict a life of 5000 hours or more.

A feature of the tube is that its operation is independent of the surrounding temperature. Tubes have been successfully operated, without attention, exposed to all kinds of weather—rain, sleet, snow,—and at temperatures as low as −20 deg. cent.

## USES OF NEON LAMPS

*Display and Advertising.* The color of the light emitted by neon makes it attractive for display and advertising purposes. D. McFarlane Moore did a great deal of pioneer work in the use of gaseous discharges in nitrogen and carbon dioxide for sign work. These were of the cold cathode type. The hot cathode neon discharge is especially adaptable for display where high intrinsic brilliancy is required.

FIG. 10

*White Light and Photography.* A neon lamp used in combination with a Cooper-Hewitt mercury lamp supplies the red which is missing in the latter, and by adjusting the mixture of the two, a good approximation to white light can be obtained. This can be observed in Fig. 10, which shows a spectrum of mercury at the top, neon in the middle, and one of skylight at the bottom.

The mercury-neon combination is particularly adapted to panchromatic photography. With daylight and panchromatic films, it is necessary to use an amber filter to obtain the correct reproduction as the films are more sensitive in the blue than the red. By adjusting the mixture of neon with Cooper-Hewitt mercury lights the illumination can be made to correct for the sensitivity of the film and a filter is no longer necessary.

## FOG PENETRATION

In heavy or foggy weather, transportation, especially boats and aircraft, is at a great disadvantage. Measurements made by Mr. Frank Benford[8] show that the absorption of the longer wavelengths in thick weather is less than that of the shorter ones. Also, general experience indicates that red can be more easily discerned than other colors. This is due not only to the fact that it has less absorption but also to its contrast with surroundings. In a fog, a great deal of the shorter wavelengths are scattered, giving rise to the glare with which every motorist is familiar. Similarly when one is looking for a light, this scattered light forms a sort of illuminated blanket which diminishes the contrast between the light source and its surroundings. When a red light is used the scattered light is minimum, thus making it easier to observe the source.

Since the hot-cathode neon lamp is one of relatively high intrinsic brilliancy, it is especially adapted for this purpose as its maximum energy occurs at about 6300 *A*°. We are indebted to Mr. Benford for the spectrophotometric analysis given in Fig. 11.

As a test on the advantages of the hot-cathode neon tube in weather of low visibility, a light of this type was mounted on a pier in the Hudson River. Observations from boats during a fog have shown that it was possible to pick up the red neon light before any of the other lights in the same vicinity were observed. These results indicate that this type of tube will be of great assistance as a marker for docks and ferry slips in the harbors and if placed on a ship it would also afford protection against collision with other vessels.

The same properties make it desirable in aviation. Its possible uses in this field include outlining a landing field, marking obstructions, and indicating a run-way. Highly concentrated tubes have been constructed for use in beacons and searchlights where a high-intensity beam is required.

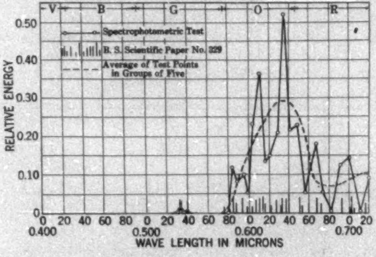

FIG. 11—SPECTROPHOTOMETRIC TEST

Neon tube No. 18,004 at 2 mm. pressure, 4.5 ampere, 121.5 volt

In general, we believe that the hot cathode neon arc is the most efficient high-intensity source of red light we have at present.

In conclusion, the authors wish to acknowledge indebtedness to their co-workers for the great assistance which they have rendered, and especially to Dr. Saul Dushman, whose interest and suggestions have been of material help in the development of these tubes.

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[8] Frank Benford, *General Electric Review*, Oct. 1926.

# Gas-Filled Thermionic Tubes

BY ALBERT W. HULL*

Non-member

## 1. INTRODUCTION AND SUMMARY

THIS paper describes a fundamental principle of thermionic gas tube operation, by which cathode disintegration may be entirely avoided. A new type of cathode is also described which requires much less heat energy than any hitherto used. With these improvements hot cathode gas tubes appear to be practical, and their fundamental characteristics as lamps, rectifiers, and "thyratrons" are briefly described.

The idea of utilizing gas in thermionic tubes is not new. It has often been proposed for lamps, rectifiers, and amplifiers. Yet up to the present time the only successful application so far as the author is aware is the "tungar" rectifier, which operates within a very restricted range of current, voltage, and gas pressure.[1] Outside of this narrow range, all attempts to use gas in thermionic tubes have resulted in unsatisfactory operation and short life. The principal symptom of failure has been disintegration of the cathode, a result so universal that it has come to be looked upon as inevitable.

The starting point of the developments described in this paper was the discovery[2] that disintegration is produced only by the impact of ions of more than a definite kinetic energy. The critical value lies between 20 and 25 volts for the common inert gases. Any precaution which avoids the presence of ions faster than this will prevent disintegration.

The simplest precaution is to adjust the circuit resistance so that the total "cathode drop" does not exceed this critical value, which may be called the *disintegration voltage*. Fortunately, the disintegration voltage is in all cases considerably above the ionizing potential, so that it is possible to obtain the ionization necessary for carrying large currents without exceeding the disintegration voltage. In properly constructed tubes the necessary and sufficient condition for keeping the cathode drop within safe limits is that the cathode electron emission shall be equal to the maximum current demand.

With this precaution, the immunity to disintegration, or sputtering, is quite general. Any type of cathode can be operated without disintegration in any inert gas, at any pressure between $\frac{1}{1000}$ mm. and 5 cm., and with any current up to the maximum vacuum electron emission of the cathode. It is doubtful whether currents very much greater than the vacuum emission can ever be obtained without disintegration.

The *maximum current* that a tube can carry appears to be unlimited except by the size of the cathode. Cathodes have been made which furnish 1500 amperes emission under conditions which promise long life; and cathodes with a normal emission of 10,000 amperes appear quite practical.

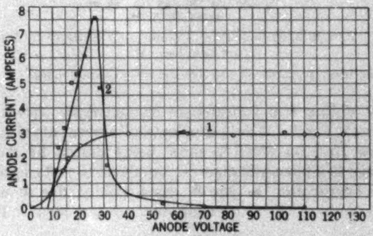

FIG. 1—VOLT-AMPERE CHARACTERISTICS OF TUNGSTEN FILAMENTS IN ARGON AT 0.030 MM. PRESSURE

Curve 1. Pure tungsten at 2450 deg. K.
Curve 2. Thoriated tungsten at 1900 deg. K.

The *maximum voltage* which can be rectified, or controlled, is limited only by the glow potential of the gas. The rectifiers and thyratrons described below operate satisfactorily at 10,000 volts, d-c., output.

*Efficiency* and *life* are inverse functions in high vacuum tubes. In gas tubes, however, it is possible to use heat-insulated cathodes which lose so little heat by radiation that the question of cathode efficiency can be disregarded and operating conditions adapted to long life. A total tube efficiency of 98 per cent, including both anode and cathode losses, at 500 volts operating potential, is easily attained under conditions which promise a life of many years. This efficiency is more than double that of the mercury arc rectifier and, like it, is nearly independent of load factor.

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[1] During the progress of this work, Wehnelt-cathode rectifiers containing low-pressure neon have been produced in Germany, and are in use in the German post office system. They have an internal voltage drop of 17-30 volts, and are capable of rectifying 1 ampere at several thousand volts. (A. Güntherschulze, "Electric Rectifiers and Valves.") A special kind of hot cathode rectifier containing low-pressure argon was described by Germerhausen, *Helios*, Vol. 26, pp. 257-60, 1920. The Wehnelt filament was operated at very high temperature, and its loss of active material compensated continually by sublimation from a rod of alkaline earth salt. The author is not aware that these rectifiers have ever come into general use.

[2] A. W. Hull and W. F. Winter, *Phys. Rev.* 21, 211, 1923. (Abstract.)

*Presented at the Joint Meeting of the New York Sections of the A. I. E. E. and the I. E. S., May 18, 1928.*

*Hot cathode controlled rectifiers*, or *thyratrons*, in which a grid is interposed between cathode and anode, have made possible the control of an output of several kilowatts by the application of one microwatt to the grid.

## 2. Disintegration Voltage

If argon at 1/10 mm. pressure is introduced into a two-electrode tube with thorium-coated cathode, one may obtain the volt-ampere characteristic shown in Curve 2, Fig. 1. The "pure electron" current at voltages below 15 is too small to show, being limited by space charge to a few milliamperes. At about 15 volts, ionization begins and the current rises rapidly, due to neutralization of the space charge by positive ions.[3] This part of the characteristic is familiar and is identical with that of a pure tungsten filament, shown in Curve 1, Fig. 1. At 25 volts, however, the current from the thoriated filament begins to decrease, and falls continually with increasing voltage to essentially zero at 125 volts. If the voltage is then gradually reduced, the current retraces its path as shown in Fig. 2. Fig. 3 shows a series of characteristics for the same tube at different filament temperatures, and Fig. 4 shows similar characteristics for a tube containing mercury vapor instead of argon.

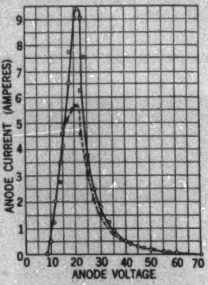

Fig. 2—Characteristic of Thoriated Filament in Argon at 1900 Deg. K.

Full curve, increasing voltage; dotted curve, decreasing voltage

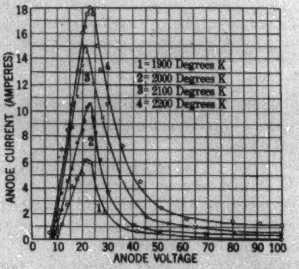

Fig. 3—Characteristics of Thoriated Filament at Different Temperatures, in Argon at 0.030 Mm.

The explanation of this unusual behavior of thoriated filaments is as follows:

The electron emission of the filament, as Langmuir has shown,[4] is due almost entirely to a single layer of thorium atoms on its surface. The positive ions, whose presence is necessary to neutralize the electron space charge, can be present in the space only by virtue of the fact that they are drifting continually toward the cathode. They strike the cathode with the energy that they have acquired in the electric field, which, in this case, is essentially the full-voltage difference between cathode and anode. As long as this voltage difference is less than 25 volts, Fig. 1 shows that the ions have not sufficient energy to injure the cathode. At 25 volts, an occasional ion is able to remove a thorium atom, and the probability of removal increases rapidly with increasing energy of the ions, *i. e.*, with increasing voltage. The loss of thorium is evidenced by decreased electron emission, which falls to essentially zero when half of the thorium layer has been removed.

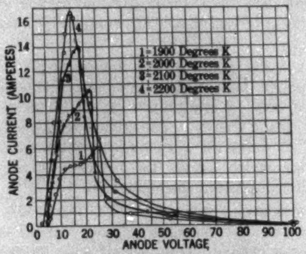

Fig. 4—Characteristics of Thoriated Filament in Mercury Vapor at about 0.005 Mm.

The curves in Figs. 1 to 4 were taken with very slowly increasing or decreasing voltage, so that at each step the amount of thorium on the surface of the filament represents an equilibrium between the rate of removal by positive ions and the rate of arrival at the surface by diffusion from the interior. If the voltage is increased rapidly, all the thorium may be removed in a small fraction of a second. Fig. 5 shows the result of applying 400 volts, d-c., through a resistance of 35 ohms, and then suddenly short-circuiting the resistance. During the first part the current (Curve *B*) is limited by the resistance to 11 amperes, which is about half the emission of the filament, and the voltage drop between cathode and anode is 15 volts (Curve *A*, deflection downward, zero line not shown). When the resistance is short-circuited, the current first rises to the full emission value and then falls rapidly to zero, while the voltage between cathode and anode rises to the full value of 400 volts. Curve *C* is a 40-cycle timing wave, from which it may be seen that the time required for the current to fall to 10 per cent of its initial value is about 1/50 sec.

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[3] The sharpness of the break at 15 volts is obscured by the alternating voltage drop along the filament. The abscissas are the voltage between the middle of the filament and the anode. The slow rise of current with further increase of voltage is due partly to this filament voltage drop, partly to a combination of more abundant ionization and secondary effects.

[4] I. Langmuir, *Phys. Rev.* 22, 357-3 [illegible] 23.

The current in Fig. 5 does not fall to zero, but to a small value just sufficient to remove thorium atoms as fast as they arrive at the surface from within. Removal of the voltage will allow the thorium layer to re-form, and the process may be repeated. The total amount of disintegration involved in each deactivation is essentially the single layer of thorium atoms, which is negligible compared with even the amount of thorium in the filament. The short-circuiting process has been repeated 1000 times in succession at 25,000 volts without any observable change in the filament.

FIG. 5—OSCILLOGRAM SHOWING EFFECT OF IMPRESSING 400 VOLTS SUDDENLY UPON THE ANODE OF A TUBE WITH THORIATED FILAMENT CONTAINING ARGON AT 0.030 MM.

Curve A = voltage between cathode and anode, deflection downward. (Zero not shown)
Curve B = current through tube
Curve C = 40-cycle timing wave

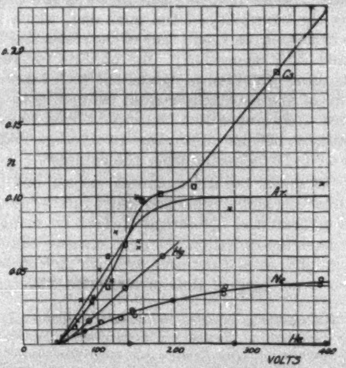

FIG. 6—NUMBER OF THORIUM ATOMS REMOVED BY AN ION AT DIFFERENT VOLTAGES (FROM PAPER OF KINGDON AND LANGMUIR.)

The most significant feature of the experiments just described is not the "circuit breaking" characteristic,—*i. e.*, the disintegration at high voltage,—but the fact that *disintegration does not occur when the voltage is below a critical value*. This fact has been confirmed by Kingdon and Langmuir,[5] who used cold thoriated filaments so that the number of positive ions striking the filament could be measured. In this way they obtained the number of thorium atoms removed per positive ion at different voltages (Fig. 6), and found that this number fell to zero at a definite voltage for each gas. These voltages were 45, 47, and 55 for neon, argon, and mercury respectively. Experiments similar to those illustrated in Figs. 1-4, with hot filaments and large positive ion currents, give somewhat lower values, *viz.*, 27 volts for neon, 25 for argon, and 22 for mercury. These values are independent of temperature over the range 1900—2300 deg. K.

The rate at which thorium diffuses to the surface of a filament may be measured.[4] This rate decreases rapidly with decreasing temperature. Since for constant electron emission the rate of gain by diffusion must be equal to the rate of loss by positive ion bombardment and other causes, it is possible to obtain an estimate of the rate of disintegration by observing the lowest temperature at which the emission is constant, and measuring the rate of activation at this temperature. No attempt has been made to carry this to the limit, but a single test will give the order of magnitude. A filament which had been operating in mercury vapor at 15 volts for 3000 hr. was chosen for the test. The temperature was adjusted to 1830 deg. K., and the tube was run for several hours, with 17 volts maximum potential and 0.015 mm. pressure of mercury vapor, until it was ascertained that it was in equilibrium. The emission was constant at 0.4 ampere. The filament was now deactivated by applying 125 volts for 10 sec., then allowed to activate at the same temperature (1830 deg. K.), without anode voltage, the voltage being applied for an instant at regular intervals to observe the rate of

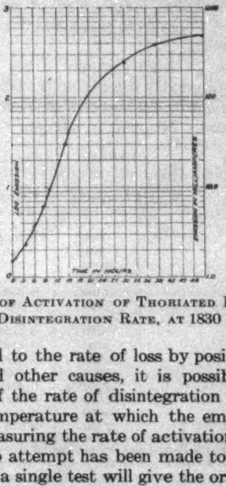

FIG. 7—RATE OF ACTIVATION OF THORIATED FILAMENT USED TO TEST DISINTEGRATION RATE, AT 1830 DEG. K.

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[5] K. H. Kingdon and I. Langmuir, *Phys. Rev.* 22, 148-160, 1923.

activation. This rate is shown in Fig. 7, in which the logarithm of the emission is plotted against time. The emission of 0.4 ampere before deactivation corresponds to a surface 9/10 covered with thorium, and from the data in Fig. 7 it is found that the surface at this stage of activation is gaining in thorium atoms at the rate $2.6 \times 10^{13} \frac{\text{atoms}}{\text{sec.}}$. This must equal the rate at which it was losing thorium atoms during operation, and this therefore represents the rate of disintegration, assuming all the loss to be due to disintegration. At this rate, a tungsten filament 1 mm. in diameter would lose 1 per cent of its weight in 140 years.

### 3. HEAT INSULATED CATHODES

The efficiency of a cathode is defined as the ratio of its electron emission to the power required to maintain it at operating temperature. It is well known that the efficiency increases with temperature, while the life, which is limited by evaporation of active material, decreases. In Table I are given a few values of efficiency and life, taken from published data[6], for common cathode materials.

In the case of high-vacuum tubes there appears to be no way of greatly increasing the efficiencies shown in Table I, except to use material of lower work function, such as caesium. No gain in efficiency can be accomplished by changing the geometrical form, as from a wire to a ribbon, since the heat-radiating area is always the same as the electron-emitting area. Any cavity which conserves radiation, such as the inside of a closely wound helix, also conserves its electrons, *i. e.*, fails to contribute appreciably to electron emission, because the electrons are prevented by the space charge from emerging.

TABLE I

EFFICIENCY AND LIFE OF COMMON CATHODES

| | Temperature (Deg. Kelvin) | Efficiency amps/watt | Life (Hours) |
|---|---|---|---|
| Oxide-Coated............... | 900 | 0.0086 | 730,000* |
| | 950 | 0.015 | 170,000* |
| | 1000 | 0.024 | 55,000 |
| | 1050 | 0.031 | 20,000 |
| | 1100 | 0.053 | 7,400 |
| Thoriated Tungsten......... | 1800 | 0.054* | 720,000* |
| | 1900 | 0.085* | 94,000* |
| | 2000 | 0.120* | 15,100* |
| | 2100 | 0.112* | 2,900* |
| | 2200 | 0.032* | 643* |
| Pure Tungsten.............. | 2300 | 0.0008 | 14,900 |
| | 2400 | 0.0018 | 2,460 |
| | 2500 | 0.0039 | 450 |
| | 2600 | 0.008 | 94 |
| | 2700 | 0.015 | 23 |

*These values are computed and correspond to ideal conditions. They should probably be reduced by a factor of about ½ to correspond with the other values, which are the most probable values from practical tests.

On the other hand, with tubes containing gas the situation is very different. Such tubes can utilize the electron emission from cavities, since the electron space charge is neutralized by positive ions. It is found that electrons freely emerge from cavities 1/8 to ¼ in. wide and 4 in. deep. The maximum useful depth has not been determined. It is thus possible to employ cathodes which are heat-insulated on the outside, whose only appreciable loss of heat is that from the open end through which the electrons emerge.

The economy which can be effected by such heat-insulation of the cathode is illustrated in Figs. 8 to 11.

Fig. 8 shows an "ordinary" type of cathode, consisting of a nickel cylinder coated on the outside with barium oxide, and heated by radiation from a tungsten filament at the center. The efficiency of this cathode is in no way different from that of a filament. Its life is somewhat longer because of the absence of burn-out possibilities, especially that due to "spotting."

Fig. 9 shows an exactly similar cathode, coated on the inside instead of the outside. The electron-emitting area is the same, but only one-third as much heat energy is required to maintain it at the same temperature, hence the efficiency is three times as high. The saving is due to the reduced heat emissivity of its outside surface. Mrs. M. R. Andrews of this laboratory has measured the emissivity of nickel that has been coated with barium carbonate and heated to various temperatures. The emissivity of the coated nickel at 1000 deg. K. varies between 0.65 and 0.85, according to treatment, while that of clean nickel is less than 0.15. Taking the emissivity of the open end, which is 1/10 of the total area, as 1, and that of the remaining 9/10 as 0.75 and 0.15 respectively, one obtains the ratio 3:1 for the total heat loss, in agreement with experiments. The life of the internally-coated cathode may also be expected to be longer by a factor of at least 10, since an evaporating barium atom has an average chance of less than 1/10 to escape from the cylinder.

Fig. 10 shows the same cathode surrounded by two heat-reflecting nickel cylinders, which further reduce the radiation from the cylindrical surface by a factor 5.[7] This makes the radiation from the surface, exclusive of the open end, only 3 per cent as much as from a black body or 4 per cent of that of a barium-oxide surface;

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[6] The values for oxide-coated cathodes are those furnished by the Western Electric Co. for International Critical Tables; those for thoriated tungsten are from Langmuir, *Phys. Rev.* 22, 396, 1923; for pure tungsten from W. E. Forsythe and A. G. Worthing, *Astrophysical Jl.*, 1925.

[7] The author is indebted to Dr. Lewi Tonks of this laboratory for the following theorem for the heat-shielding efficiency of metallic surfaces: Assume $K$ concentric metal surfaces all alike, of emissivity $e$, sufficiently close together so that the difference in radii may be neglected. The heat necessary to maintain the inner surface at constant temperature is $\frac{e\,E}{2\,k - 1 - (k - 1)\,e}$ where $E$ is the energy radiated by a black body of the same size and temperature. When $e$ is small, as in the present case, this reduces to $\frac{e\,E}{2\,k - 1}$.

and the total loss, including the open end, 1/6 as much as the cathode of Fig. 8. There is little to be gained by further shielding of the surface, since perfect shielding would reduce the ratio only to 1/8. A further gain of twofold could be obtained by doubling the ratio of length to open end area, which is practical.

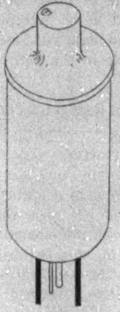

Fig. 8

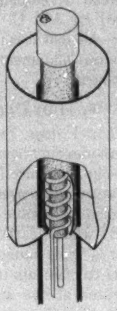

Fig. 9

Fig. 8—Typical Externally-Coated Cathode, Heated by Radiation from a Tungsten Filament at the Center

Fig. 9—Internally-Coated Cathode of Same Dimensions as Fig. 8

The heat loss is only one-third as much

A greater gain is obtained, however, by the method illustrated in Fig. 11. This cathode is the same as Fig. 10 except that 16 radial vanes have been added, which are coated on both sides with active material, and form part of the electron-emitting surface. Their presence requires no additional heat, but increases the electron-emitting area fourfold. Hence the total efficiency of this cathode is 24 times that of the cathode shown in Fig. 8. It is therefore practical to operate it at a temperature of 1000 deg. K., which would give only 24 milliamperes per watt for a filament (see Table I), but for the shielded cathode gives 600 milliamperes per watt.[8] This corresponds to a circuit loss at full load of only 1.5 volts, which is nearly negligible compared with the arc drop loss of about 10 volts. The life of this temperature would be 55,000 hr., or about 7 years for a filament, and should be greater for a cylinder, which cannot burn out and cannot easily lose its active material.

The same structure is obviously applicable to other types of cathodes, such as thorium-coated or cerium-coated tungsten or molybdenum.

Exact data are not yet available to prove that these very high values of life and efficiency are attainable. Efficiencies very close to those predicted have been obtained. For example, cathodes requiring but 200 watts give 250 amperes emission at an estimated temperature of 1100 deg. K. (cf. Figs. 20, 21). This is very close to 24 times the efficiency (53 milliamperes per watt) of a similar filament at the same temperature. It is obvious, of course, that the 200 watts merely supply the heat losses and keep the cathode at operating temperature when idle. The energy necessary to liberate the electrons, which amounts to about one watt per ampere or 250 watts total, is supplied by the kinetic energy and heat of condensation of positive ions and excited atoms and the back radiation from the arc stream. If one may speak of this energy as useful, as contrasted with the 200 watts which are wasted, the efficiency of heat utilization of these cathodes is about 55 per cent.

As regards life, the only information available is that tubes which have been operating continuously except Sundays for 6 months show no change. It is wholly probable that unexpected factors, such as chemical action, crystallization, or gradual evolution of gas, will terminate life in present tubes at times much shorter than those calculated. But it seems possible that, with development, these long life values may be realized.

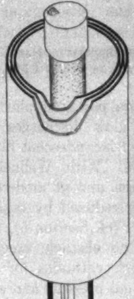

Fig. 10

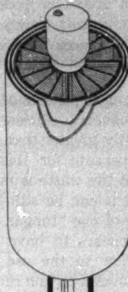

Fig. 11

Fig. 10—Same Cathode as Fig. 9 Plus Heat Shielding Which Further Reduces the Heat Loss by a Factor One-Half

Fig. 11—Same as Fig. 10 Plus 16 Electron-Emitting Vanes which Increase the Electron Emission by a Factor 4

The heat loss remains unchanged

## 4. Hot Cathode Lamps

The use of the hot cathode glow discharge for illumination was proposed by D. McFarlane Moore[9] in 1905. Lederer,[10] in 1914, suggested the use of a Wehnelt cathode in place of Moore's carbon filament for such a glow lamp, and Skaupy,[11] in 1915, suggested a tungsten filament.

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[8] This does not include the cooling effect of the electron emission which, however, appears to be very nearly compensated by the heat of condensation of positive ions and activated atoms and the radiation from the arc.

[9] Moore, U. S. Pat. 1010668.

[10] Dederer, U. S. Pat. 1461921.

None of these hot cathode lamps appear to have come into general use. In the case of the carbon and tungsten filaments a sufficient reason was cathode inefficiency. A 10-mil tungsten filament at 2500 deg. K. requires 236 watts of heating power per ampere electron emission. The maximum work that this electron emission can do in a 110-volt lamp is 110 watts per ampere, or 29 per cent of the total power supplied. The light-producing efficiency of glow discharges is not sufficiently greater than that of incandescent filaments to compensate for this waste. With Wehnelt type cathodes the waste is much less, and at moderate gas pressure it can be still further reduced by taking advantage of the "tungar effect" (cf. Section 5), so that there appears to have been no obstacle except disintegration to the use of such cathodes for lamps, at least over a certain range of gas pressure and voltage.

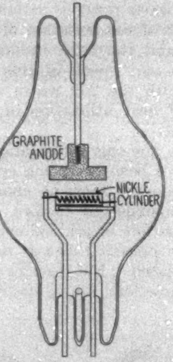

FIG. 12—TUNGAR TYPE RECTIFIER, WITH OXIDE-COATED CATHODE IN MERCURY VAPOR AT ABOUT 1 MM.

Both of these limitations, disintegration and inefficiency, may be removed by the measures described in Sections 2 and 3 above, and it would appear that there remains no fundamental impediment to the utilization of such hot cathode glow discharges for illumination at any pressure and in any gas that does not dissociate or attack the cathode chemically. Two subsidiary problems, disappearance of the gas and blackening of the bulb, appear to be intimately connected with cathode disintegration[12] and may be expected to disappear with it. The test data available confirm this view. Tubes containing cathodes like those shown in Fig. 9 have been operated for 2000 hr. in Hg. vapor at 0.015 mm. with no visible blackening; and the neon lamps tested by Mr. C. G. Found show no measurable change in neon pressure after 3000 hr.

Whether or not these glow discharges will make useful lamps is quite another problem and depends on such factors as cost, luminous efficiency, color of light, convenience of operation, and degree of commercial development. Some of these factors are discussed by Mr. C. G. Found in an accompanying article. All that it is intended to point out here is that there is no fundamental obstacle in the path of such development.

## 5. HOT CATHODE GAS RECTIFIERS

*A. Low-Voltage Tungar Type.* Ordinary Wehnelt type cathodes may be operated in mercury vapor at from 1- to 3-mm. pressure for surprisingly long life at high temperature and correspondingly high efficiency. For example, a half-wave rectifier of the type shown in Fig. 12, whose cathode is a barium-coated nickel cylinder ¼ in. in diameter by ⅝ in. long, requiring only 25 watts to maintain it at operating temperature, may be operated at five amperes average rectified output for 4000 hr. If operated under the same conditions in Hg. vapor at 1/100-mm. pressure, the life is less than 20 hr. The difference is due to the protective action of the gas, which tends to prevent evaporation of both barium and nickel in the same manner as in gas-filled lamps, and also appears to cause the return to the cathode of nearly all evaporating barium atoms, presumably as a result of ionization by "collisions of the second kind" with excited mercury atoms. This is evidenced by the slow rate of evaporation of barium as compared with nickel. After 4000 hr. the cathode of Fig. 12 may be reduced by evaporation to a mere lacework, yet retain its full electron-emitting activity. If operated at the same temperature in vacuum, or low-

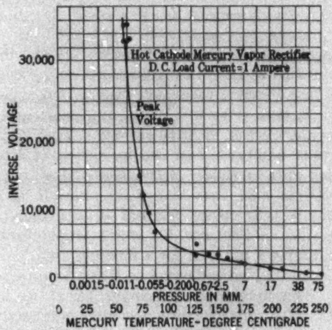

FIG. 13—VOLTAGE (PEAK VALUES) AT WHICH ARC-BACK OCCURS AT DIFFERENT PRESSURES OF MERCURY VAPOR IN THE TUBE SHOWN IN FIG. 14

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[11] Skaupy, German pat. 302806.

[12] Cf. Contributions from Res. Lab. of G. E. Ltd., *Phil. Mag.* 41,685,1921; J. Fischer, *Fortschritte d. Chem.* 19, 1, 1927.

pressure gas, the rate of loss of barium is high compared with that of nickel, so that the electron emission is permanently lost in 20 hr.

This protective action appears to be identical with that which gives to the "tungar" rectifier its distinctive features, and these high mercury pressure tubes are to be classed as tungars. They are capable of rectifying slightly higher voltages than argon-filled tungars, a rectified d-c. output of 500 volts being possible with pressures between 1 and 3 mm. (cf. Fig. 13).

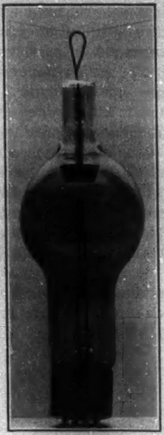

FIG. 14

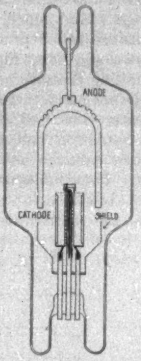

FIG. 16

FIG. 14—SMALL HIGH-VOLTAGE MERCURY VAPOR RECTIFIER, CAPABLE OF WITHSTANDING 20,000 VOLTS

FIG. 16—CROSS-SECTION SKETCH OF A 75-AMPERE GLASS RECTIFIER FOR 100—10,000 VOLTS

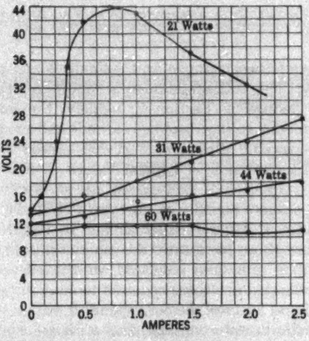

FIG. 15—ARC-DROP IN RECTIFIER OF FIG. 14, AT 0.005 MM., WITH DIFFERENT FILAMENT TEMPERATURES

The watts refer to filament heat

*B. High Voltage.* For high-voltage rectification, above 1000 volts, it is necessary to use a gas pressure so low that its protective action is negligible. The maximum voltage between anode and cathode which a rectifier can withstand appears to be identical with the sparking potential of the gas at the existing pressure, electrode material, and effective electrode distance. The effective distance is that between the pair of points which has the lowest sparking voltage. In the case of rectifiers, it is not limited to actual electrode distances, since the presence of positive ions can distort the electric field so that the full voltage may exist in a thin "sheath," a small fraction of a millimeter thick, next to the cathode[13] (the anode of the rectifier). At high gas pressures, at which the spark length corresponding to minimum sparking potential is less than

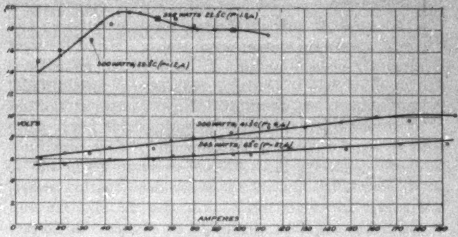

FIG. 17—D.-C. VOLT—AMPERE CHARACTERISTICS OF FIG. 16 RECTIFIER AT DIFFERENT MERCURY PRESSURES

Watts refer to cathode heat. Note that the 228- and 300-watt curves at 22.5 deg. cent. are identical, showing that the high drop is due to low vapor pressure and not low cathode temperature

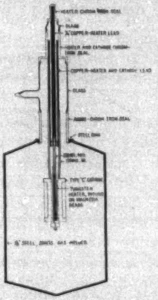
GLASS
COPPER-HEATER LEAD
HEATER AND CATHODE CHROM-IRON SEAL
COPPER-HEATER AND CATHODE LEAD
GLASS
ANODE-CHROM IRON SEAL
STEEL RING
TYPE "C" CATHODE
TUNGSTEN HEATER, WOUND ON MAGNESIA BEADS

FIG. 18—CROSS-SECTION OF METAL RECTIFIER, SAME CATHODE AS FIG. 16

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[13] I. Langmuir, *Science*, 58, 290, 1923; *Jl. Franklin Inst.*, 196, 751, 1923; *G. E. Rev.* 26, 731, 1923.

the actual distance between electrodes, the space charge will automatically adjust itself to give this optimum distance. There is no lower limit to the thickness of this sheath. Hence it is easily seen that the arc-back voltage should be constant and equal to the minimum sparking potential of the gas for all gas pressures higher than a certain value. This limiting value is the pressure which corresponds to the minimum sparking potential between the electrodes.

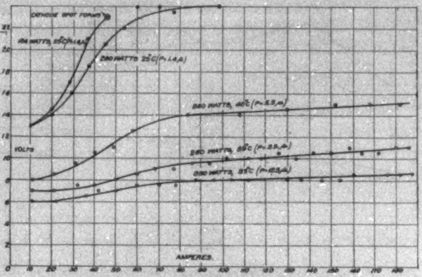

FIG. 19—D-C. CHARACTERISTICS OF METAL RECTIFIER SHOWN IN FIG. 18

The 186-watt curve shows a condition of insufficient emission, resulting in high voltage drop and cathode spot

For pressures lower than this limiting value, the sparking potential is increased by shortening the distance and can be decreased only by lengthening the distance. But there is a definite limit to the possible length, set by the dimensions of the tube. Hence the arc-back voltage increases with decreasing pressure, and at any given pressure, is equal to the sparking potential of the gas at that pressure and at a spark length equal to the maximum possible path between electrodes. The steepness of the sparking potential-pressure curve at low pressures is well known, and we should expect a corresponding steepness of arc-back voltage *vs.* pressure. Fig. 13 shows the results of arc-back measurements for the tube shown in Fig. 14. The abscissas are mercury vapor pressure in thousandths of a mm., the ordinates the maximum voltage which the tube could rectify without arcing back. The voltage values are maximum or peak voltages between anode and cathode, *i. e*, the maximum reverse voltage strain which the tube can withstand. These values are quite reproducible. It will be noted that the curve is still rising rapidly at the lowest pressure used. A limiting pressure must eventually be reached where, on the one hand, there is not sufficient gas to furnish the necessary ions, and, on the other hand, the strength of the insulation and the presence of "cold cathode" electron emission set a limit to the voltage that can be used. These limits are functions of tube geometry, and cannot be stated at present.

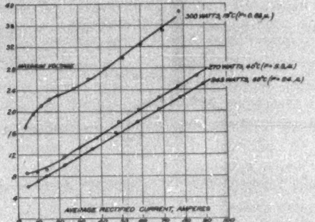

FIG. 20—MAXIMUM VOLTAGE DROP (TUBE VOLTMETER READINGS) IN GLASS TUBE WITH ALTERNATING PLATE VOLTAGE, AS FUNCTION OF AVERAGE RECTIFIED CURRENT

Note that at 19 deg. cent. the tube cannot carry more than 15 amperes without exceeding the disintegration voltage. (Tube shown in Fig. 16)

In the current-carrying direction the potential difference between anode and cathode is and must be very low. This is the fundamental condition for cathode life, as defined in Section 2; namely, the maximum instantaneous voltage between cathode and anode in the current-carrying direction must not exceed the "disintegration voltage." Typical values of this voltage drop as a function of load current are shown in Fig. 15 for a ½ ampere rectifier of the type of Fig. 14, and in Fig. 17 for a larger rectifier similar to Fig. 16. The values are those for steady d-c. operation, at the mercury vapor pressures indicated on the curves. The watts indicated are those required to heat the cathode. Figs. 20 and 21 give the corresponding values of maximum instantaneous voltage drop with a-c. operation, measured with a vacuum tube voltmeter. Fig. 19 shows similar characteristics for a tube of the form shown in Fig. 18, in which the iron envelope acts as anode; and Fig. 22 those of a tube similar to Fig. 16, but with a larger and better cathode, of the type shown in Fig. 11. Attention is called to the low values of heating watts shown in this figure.

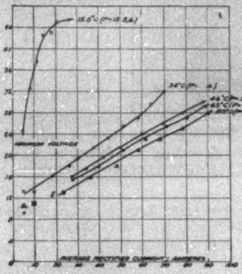

FIG. 21—SAME CHARACTERISTICS AS IN FIG. 20, FOR METAL TUBE, FIG. 18

It will be noted that high gas pressures favor low arc drop. This is due to the increased probability of ionization by processes other than electron impact. The total voltage between anode and cathode may fall as low as 4 volts in mercury vapor at 1 or 2 mm. On the other hand, too low a gas pressure requires that the voltage drop shall rise in order to furnish the requisite number of positive ions, and it may rise above the disintegration value. The increase is probably to be associated with anode drop rather than cathode drop. But a considerable fraction of the ions will strike the cathode with the energy of the full voltage difference, and will ruin the cathode if this voltage is above the disintegration value. The 15-deg. curve in Fig. 21 shows such a condition. Fig. 17 shows two low-pressure curves at the same pressure, but with different cathode temperatures. The curves are identical, proving that the increased voltage drop is a function of gas pressure and not electron emission. The high maximum voltages observed in the a-c. characteristics (Figs. 20 and 21) demand consideration. Examination with an oscillograph showed that they are due to sharp peaks occurring at the beginning of each cycle. It is seen that the maximum safe rectified current at 40 deg. cent. (5.5 microns) is only 65 amperes for the glass tube and 50 for the metal tube.

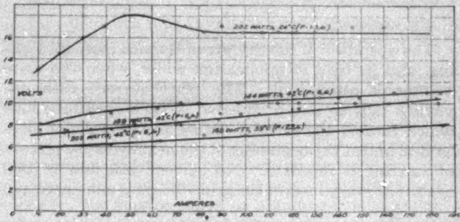

FIG. 22—D-C. CHARACTERISTICS OF TUBE SIMILAR TO FIG. 16 WITH CATHODE LIKE FIG. 11

Note that the 42 deg. curves for 189 and 202 watts are identical showing that 189 watts are sufficient for 190 amperes emission. At 144 watts the cathode temperature is too low, and the deficiency is made up by increased arc drop

The effect of low cathode temperature demands special attention. In the tests thus far described the cathode temperature has been such that the electron emission was more than sufficient for the maximum demand. If the temperature is lowered to the point where the emission is insufficient—that is, where the *I R* drop with maximum emission is less than the impressed voltage,—it is obvious that the voltage drop in the tube must rise. With a pure tungsten cathode, the tube continues to operate with this high-voltage drop (c f. Curve 2, Fig. 1), with correspondingly rapid disintegration. Thorium-coated cathodes lose their thorium coating and cease to operate (see Figs. 1 to 4). The behavior of Wehnelt cathodes is a combination of these two effects, plus an increase in emission due to rise of temperature resulting from the bombardment. If the temperature of the cathode is not too high, an excess voltage will deactivate it exactly as in the case of thorium-coated cathodes, and it will remain inactive as long as the voltage is maintained, but will regain its activity if the voltage is removed for a short time. This is the best evidence available that the activity of these cathodes is due to a monatomic layer of barium atoms, presumably held by a layer of oxygen as in the case of caesium-coated filaments.[14] With higher cathode temperature or high voltage, the cathode is usually heated locally by the bombardment, with rapid fluctuation of emission and dancing of a "cathode spot." An example of such a spot is seen in the upper curve in Fig. 19. On the other hand, an excess voltage drop below the critical value may cause the cathode temperature to rise uniformly until the requisite emission is obtained, and the equilibrium cathode drop is that which is just sufficient to maintain this temperature. Fig. 15 shows such a condition for a small tube, and the 144-watt curve in Fig. 22, a similar condition in the large glass tube. The agreement of the two sets of points on the lower 42-deg. curve in Fig. 22, for temperatures corresponding to 188 and 203 watts respectively, shows that the emission at 188 watts is sufficient. This is an emission of one ampere per watt supplied to the cathode. The total tube efficiency, including the arc drop of 10 volts, is 89 per cent at 100 volts for d-c. operation. For operation as a rectifier two cathodes are needed, making the total efficiency at 40 deg. cent (5.5 microns pressure) 88 per cent at 100 volts. With the same cathode temperature and the mercury at 59 deg. cent (23 microns) the efficiency as rectifier is 90 per cent at 100 volts, and 98 per cent at 500 volts.

From the test data available the operating behavior of these rectifiers appears to agree with that to be expected from the characteristics. Tubes like Fig. 14 have been operated satisfactorily for periods of 1000 hr. at 10,000 volts, d-c., output. The larger glass rectifiers, as in Fig. 16, have been tested for periods of 100 hr. at 1500 and 3000 volts, with individual outputs of 75 to 150 amperes average rectified current. It is expected that they, too, will operate satisfactorily at 10,000 volts with full output, but this has not yet been tested.

## 6. THYRATRONS

The name thyratron, (from the Greek θύρα,—a door), has been suggested for an arc whose starting can be controlled by a grid. It has been known for a long time that arcs could thus be controlled.[15] They have been the subject of an exhaustive study in this laboratory, under the direction of Dr. Langmuir, for several years, and the results of these investigations will soon be published by Langmuir and his associates.[16] Only the specific characteristics of hot-cathode thyratrons similar to the above rectifiers, which are very simple, will be described here.

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[14] K. H. Kingdon, *Phys. Rev.*, 24, 510-22, 1924.

[15] I. Langmuir, U. S. Pat. 1,289,823, Dec. 1918.

Figs. 23 and 24 show typical hot cathode thyratrons of this type. Their structure is identical with that of pliotrons except for the form of cathode and the limitations of filament voltage and grid size noted below.

Their characteristics are also the same as pliotrons *when no plate current, or very little, is flowing.* The distribution of potential in the tube is then obviously the same as in a high-vacuum tube. The amplification factor is defined, as in ordinary vacuum tubes, as the ratio of plate to grid voltage that will keep the plate current at a constant small value. This factor determines at what grid voltage the tube will "start."

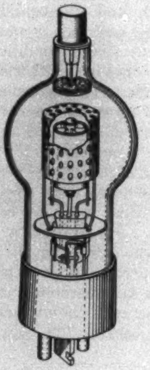

FIG. 23

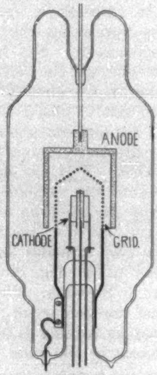

FIG. 24

FIG. 23—TYPICAL HOT CATHODE THYRATRON

The grid must not emit electrons, hence its large size

FIG. 24—COMPLETELY SHIELDED THYRATRON

This type of structure gives reproducible characteristics and favors rapid disappearance of ions

As soon as plate current begins to flow the similarity to pliotrons ends. Such factors as mutual conductance and plate resistance do not exist, for the grid is instantly surrounded by a sheath[13] of positive ions, and has no further effect on the current.

This sheath, in general only a fraction of a millimeter thick, contains the whole voltage drop between the grid and the space surrounding it. Changing the grid voltage merely changes the thickness of the sheath, and has no effect on the potential of the rest of the space. Hence the grid is powerless to stop the plate current, once it is started, or to influence it appreciably. It can be stopped only by removing the plate voltage.

The function of the grid is therefore obvious. It is a trigger. If it is desired to turn on a current and allow it to flow thereafter, the thyratron enables this to be done by a very small amount of power. The total energy required to turn on a kilowatt in a tube similar to Fig. 23 is less than $10^{-12}$ watt-seconds (1/10 microwatt acting for 10 microseconds).

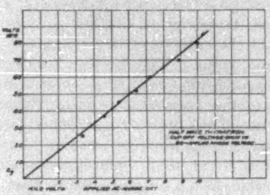

FIG. 25—CONTROL CHARACTERISTIC OF THYRATRON SHOWN IN FIG. 23

Showing grid voltage at which current starts, as a function of anode voltage

The operation of the thyratron is much more interesting, and its field of application wider, when the plate voltage is alternating. The plate current then obviously falls to zero at the end of each cycle, the ions which formed the sheaths diffuse to the walls or electrodes, and at the beginning of the next cycle the process of starting is repeated. No current will flow in this cycle if at every instant the grid voltage is more negative than $\frac{E_p}{\mu}$ where $\mu$ is the amplification factor and $E_p$ the instantaneous plate voltage. If at any instant the grid voltage is less negative than this value the plate current will start and flow for the rest of the cycle. The magnitude of the plate current, once started, is limited only by plate voltage and load resistance, not by grid voltage. The *average* plate current, however, is completely determined by grid voltage, since it may allow plate current to flow during any desired number

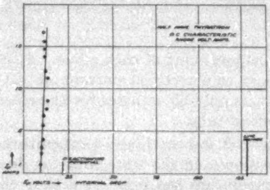

FIG. 26—VOLTAGE DROP IN THYRATRON AS FUNCTION OF CURRENT

of cycles in each second, or any desired fraction of each cycle. With high-frequency plate voltage the period of averaging may be very short, and if it is short compared with the period of the phenomenon to be observed an essentially continuous control is obtained. Thus audio waves of frequencies up to 5000 may be reproduced with considerable faithfulness by a thyratron with 50,000-cycle plate voltage.

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[16] See also L. Dunoyer and P. Toulon, *Comptes Rendus*, p. 179, 1924; *Jl. de Phys.*, 5, 257-68, 289-303, 1924.

These hot cathode thyratrons have the same general characteristics as the rectifiers described above, and the same requirements, especially as regards disintegration voltage. In fact, once the current is started, the grid has no more effect than a glass wall, and the behavior of these thyratrons is almost identical with that of similar tubes without grids.

In addition, the following special requirements are essential for thyratrons:

1. The maximum filament voltage must not exceed the ionization potential, unless the filament acts as a heater only and is wholly enclosed. Even then, it is hard to prevent the ions formed by this voltage from diffusing into the space around the grid, and forming a sheath which nullifies the effect of grid voltage. This requirement makes it impracticable to convert most standard pliotrons into thyratrons by introducing gas, except those whose rated filament voltage is below 7½ for mercury vapor and below 10 in case argon is used.

2. The grid must not emit electrons. For such electrons may fly freely to the anode, no matter what the grid potential, and produce ions which will sheathe the grid and make it powerless. The maximum grid emission which can be tolerated depends on the probability of ionization, and hence on voltage and geometry, but may be taken as about one milliampere for low-voltage operation and one microampere for high voltage. The size of the grid in Figs. 23 and 24 is dictated by the requirement of grid emission. Similar tubes with smaller grids are operative when new, but become inoperative when the grid has become coated, as it usually does eventually, with active material from the cathode.

3. The grid must shield the whole cathode from the anode. In high vacuum tubes the protrusion of 5 per cent of the filament beyond the end of the grid results only in 5 per cent "zero" current, which has no effect on operation except to reduce the useful power by this amount. As a thyratron such a tube is nearly worthless. It will pass full current at all reasonable grid voltages, since a small fraction of one per cent of the total emission is sufficient to produce ions that will sheathe the grid. The uniformity of the grid is more important than in high vacuum tubes, since the amplification factor is determined entirely by the largest hole.

This requirement of complete shielding makes even the small pliotrons of most standard types unsuitable for conversion into thyratrons by introducing gas, because of the shortness of the grids.

4. The gas pressure must not be so high that the positive ions persist for a half cycle. This is a question of diffusion. The time required for the ions to diffuse to the electrodes and walls depends on the geometry of the electrodes, as well as on the gas pressure. In the tube shown in Fig. 23 the maximum pressure of mercury vapor for 60-cycle operation is 0.040 mm., while a tube similar to Fig. 24 is operable under the same conditions with 1 mm. pressure of mercury.

5. A full-wave hot cathode thyratron with two anodes in the same bulb will obviously give large positive ion currents to the grids, unless sufficient shielding is provided. Rectifiers of the same type have inherent anode sputtering, but are operable under conditions which would make thyratrons inoperable.

6. Tubes containing vapors which are ionized by contact with the cathode, like *Cs*, *Rb*, and *K*, give positive ion sheaths around the grid when the grid is negative, making operation as thyratrons difficult or impossible.

These limitations do not apply to tubes whose grid mesh is so fine that the positive ion sheaths overlap under operating conditions. These tubes can be operated in the presence of positive ions, but their characteristics are quite different from those under discussion, and they will not be considered here. The most significant operating characteristics of these thyratrons are amplification factor and voltage drop. Fig. 25 shows the amplification factor curve of a thyratron similar to Fig. 23. The values of grid voltage plotted are the "starting" voltages, *i. e.*, the values that mark the line between no current and full current. Fig. 26 shows the voltage drop as a function of load. It does not differ appreciably from that of rectifiers.

In obtaining the data presented in this paper I have had the assistance of the whole research staff, but especially of Messrs. W. F. Winter, E. P. Lawsing, H. C. Steiner, and W. A. Ruggles, whose able cooperation I gratefully acknowledge.

# The Drive of Tandem Rolling Mills

BY A. F. KENYON*

Associate, A. I. E. E.

***Synopsis.**—The paper briefly discusses the development of the tandem type of rolling mill and the requirements of electrical drives for such mills, and presents methods of calculation of power requirements.*

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CHANGING conditions in the steel rolling mills of this country have caused the development and widespread application of what are quite commonly termed "tandem" rolling mills. The tandem type of mill has the advantages of great flexibility, high tonnage output, low labor costs, compactness of layout, and uniform quality of product. This type has been applied successfully to the production of thin flat stock up to 50 in. wide, rod, bar, merchant, and structural shapes. In this type of mill, the several finishing stands, and in some recent installations the roughing stands also, are closely spaced in a continuous line and are individually driven by separate motors. The length of the billets and the spacing between stands are such that a single piece of steel may be in several stands at one time, and for periods of several seconds. It is therefore essential to the successful operation of such a tandem mill that the speeds of the several driving motors be susceptible of easy and accurate adjustment, in order that stretching or looping of the steel between stands may be kept within limits.

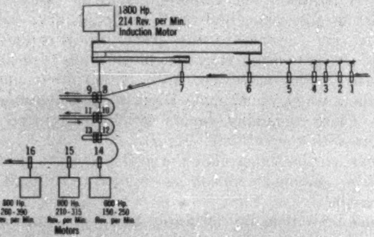
1800 Hp.
214 Rev. per Min.
Induction Motor
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
800 Hp.
260-390
Rev. per Min.
800 Hp.
210-315
Rev. per Min.
600 Hp.
150-250
Rev. per Min.
Motors

FIG. 1—14-IN. STRIP MILL AT CUYAHOGA WORKS OF AMERICAN STEEL AND WIRE COMPANY

Illustrating first application of d-c. adjustable-speed motors to tandem finishing stands. Installed 1908-9

### DEVELOPMENT OF TANDEM OPERATION

During 1908-9, the American Steel and Wire Company installed at its Cuyahoga Works a 14-in. mill which is of considerable interest in that it was the first electrically driven mill for the rolling of wide strip material, and that it was the first application of separate d-c. adjustable speed motors for the individual drive of each of the three tandem finishing stands. The arrangement of the stands is shown by Fig. 1. The distance from stand 14 to 15 was 12 ft. and from stand 15 to 16 was 15 ft. The three finishing stands were driven by direct-coupled 575-volt d-c. motors of 600 hp., 150/250 rev. per min.; 800 hp., 210/315 rev. per min.; and 800 hp., 260/390 rev. per min., capacity respectively. At the top speed of 390 rev. per min. on stand 16 motor, the delivery speed was approximately 1325 ft. per min. The mill has a range of capacity from 18 gage strip up to about 4 in. wide to 14 gage material up to about 10 in. wide. In its arrangement of the finishing stands the mill varies but little from more recent designs.

With the more recent installations the trend has been toward the elimination of stands in train, with final development of the present mills in which the stands are arranged in one continuous line. As an intermediate step in the development, Fig. 2 is included to show the layout of the semi-continuous mill of the West Leechburg Steel Company. The equipment and operation of this mill were described in a paper read before the April 1924 Convention at Birmingham by Jones and Wilson.

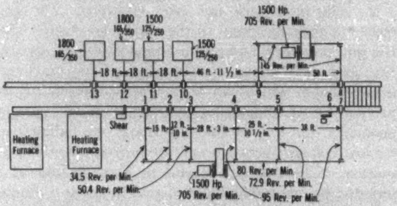
1500 Hp.
705 Rev. per Min.
1800
165/350
1800
165/350
1500
125/250
1500
125/250
18 ft.
18 ft.
18 ft.
46 ft. - 11 1/2 in.
145 Rev. per Min.
50 ft.
13
12
11
10
9
8
1
2
3
4
5
6
7
Heating Furnace
Heating Furnace
Shear
15 ft.
12 ft. 10 in.
28 ft. - 3 in.
25 ft. 10 1/2 in.
38 ft.
34.5 Rev. per Min.
50.4 Rev. per Min.
1500 Hp.
705 Rev. per Min.
80 Rev. per Min.
72.9 Rev. per Min.
95 Rev. per Min.

FIG. 2—20-IN.—16-IN. SEMI-CONTINUOUS STRIP MILL AT WEST LEECHBURG STEEL COMPANY

The four finishing stands are individually driven by two 1500-hp. and two 1800-hp. d-c. motors

The Acme Steel Company has a mill very similar in equipment to the West Leechburg mill, but in which the stands are arranged in a single line, eliminating the broadside transfer. Also the two intermediate stands are much closer together and are driven by adjustable-speed direct-current motors. This arrangement permits of additional flexibility and permits the rolling

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of finished strips up to 600 ft. or longer. Fig. 3 shows the arrangement of the mill and driving motors.

Latest designs show a tendency to apply individual motor drives to the roughing as well as the intermediate and finishing stands. A mill for the production of strip up to 50 in. wide, construction of which will soon be completed, consists of eleven roll stands, the first four driven by wound-rotor induction motors, and the last seven driven by d-c. motors. The total capacity of the eleven motors is 21,800 hp. A similar eleven stand mill will be driven by one constant-speed motor and nine adjustable-speed d-c. motors.

On the tandem stands of the mills so far discussed in this paper, d-c. adjustable-speed motors have been applied. The question may logically be asked: Why not use some type of alternating-current adjustable-speed drives? To answer this question we should consider first the suitability of such machines for tandem mill operation, and second the relative cost as compared to other drives.

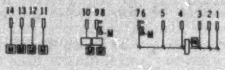

FIG. 3—20 IN.-16 IN. STRIP MILL AT ACME STEEL COMPANY

The vertical edgers and the intermediate and finishing stands are driven by d-c. motors

| Pass | Diam. | Rev. Per. Min | D. to next pass | Motor hp. |
|---|---|---|---|---|
| 1 | 20″ | 35 | 15′–6″ | |
| 2 | 20″ | 35 | 16′–7″ | |
| 3 | 20″ | 50 | 33′–0″ | |
| 4 | 20″ | 95 | 30′–0″ | 1500 |
| 5 | 20″ | 79 | 38′–7″ | |
| 6 | . . | . . | 8′–0″ | 100 |
| 7 | 20″ | 95 | 66′–0″ | |
| 8 | . . | . . | 8′–0″ | 100 |
| 9 | 16″ | 76–152 | 18′–0″ | 1500 |
| 10 | 16″ | 100–200 | 77′–0″ | 1800 |
| 11 | 16″ | 125–250 | 18′–0″ | 1800 |
| 12 | 16″ | 125–250 | 18′–0″ | 1800 |
| 13 | 16″ | 185–370 | 18′–0″ | 1800 |
| 14 | 16″ | 185–370 | | 1800 |

It is a requirement of any continuous mill, in which steel is in two or more stands simultaneously, that the product of delivery speed and cross sectional area of steel after the pass must be the same for each pass of the mill, else the steel will be stretched or a loop formed between stands. Speed adjustments must therefore accompany any changes in the drafts made in the various passes. Mill operators, in purchasing tandem mill drive equipment, have commonly specified that the motors should have a speed regulation of not more than 2 per cent. Analysis shows, however, that the actual speeds while steel is in the mill, rather than the difference between the friction and rolling load speeds, determine the amount of looping or stretching which will take place. Regardless of the friction-load speeds, each motor will quickly assume its loaded speed as soon as the steel enters the rolls, and if the loaded speeds of each of the several stands are in the correct relation for the reductions being made, there will be no stretching or looping. From this standpoint successful operation can and is being obtained with motors having as much as 8-10 per cent speed regulation on the finishing stands. However, with motors of flatter speed characteristics, the speeds of the several motors may be more accurately set at no-load, and speed changes due to load variations caused by changes in draft, temperature of steel, etc., are kept at a minimum. This makes a comparatively flat speed characteristic in the motors very desirable. Most operators therefore insist on motors of flat speed characteristics.

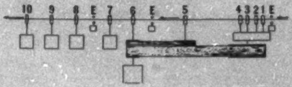

FIG. 4—10-IN. STRIP MILL OF LACLEDE STEEL COMPANY ILLUSTRATING THE USE OF A MULTI-STAND ROUGHING MILL IN TANDEM WITH INDIVIDUAL MOTOR DRIVEN FINISHING STANDS

| Pass | Diam. | Rev. per min. | Motor hp. |
|---|---|---|---|
| Edger | . . | 275/825 | 100 |
| 1 | 12 | 31/63 | . . |
| 2 | 12 | 45/90 | . . |
| 3 | 12 | 61/122 | . . |
| 4 | 12 | 90/181 | . . |
| 5 | 11 | 123/249 | . . |
| Edger | . . | 400/1600 | 35 |
| 6 | 10 | 198/400 | 1500 |
| 7 | 10 | 185/470 | 600 |
| Edger | . . | 400/1600 | 35 |
| 8 | 10 | 270/635 | 600 |
| 9 | 10 | 395/825 | 720 |
| 10 | 10 | 480/1000 | 720 |

There is a type of mill, such as the 10-in. strip mill of the Laclede Steel Company, Alton, Illinois, Figs. 4 and 5, where motors of good speed regulation are quite necessary. In this mill, the six roughing stands are driven by a 1500-hp. 198/400-rev. per min. motor, and the four finishing stands are driven by individual motors of 600 hp. and 720 hp. capacity. The billets are of such length that one piece may be in all stands of the mill simultaneously.

For illustration, assume that the speed regulation of the 1500-hp. motor is 5 per cent and that the speed-load curve is a straight line. Further assume that the friction load is 100 hp. and that the rolling load of each stand is 300 hp. making a total load of 1900 hp. when metal is in all stands. In order to avoid stretching of the steel between stands 6 and 7, it is necessary to have the delivery speed of stand 6 equal to or greater than the take-up speed of stand 7. That is, the speed of the 1500-hp. motor when carrying 1900 hp. load must give a delivery speed to stand 6 at least equal to the take-up speed of stand 7. But, as the end of the strip leaves stands 1, 2, 3, 4, and 5, in succession the load on the 1500 hp.-motor is reduced, the speed increases, and a loop is formed. Table I shows the data for a particular rolling schedule, and indicates that nearly five ft. more material will be delivered from stand 6 than is taken up by stand 7, during the interval between the time when the tail end of a piece leaves stand 1 and the time it leaves stand 6. Remember, too, that this is on the basis that the delivery speed of stand 6, when steel is in all the roughing stands, is exactly equal to the take-up speed of stand 7, and that there is no loop formed until the tail end of the piece leaves stand 1. If, as is quite often the case, in order to avoid all possibility of stretching the normal delivery speed of stand 6 with the roughing mill full is slightly in excess of the take-up speed of stand 7, there will be an initial loop between stands 6 and 7 before the steel leaves stand 1. Then by the time the steel leaves stand 6, the loop may have become so large as to be unmanageable. When this motor was first installed, the speed regulation was of the order of 7-8 per cent, due to a misadjustment. Considerable trouble was experienced due to the excessive looping of steel, until adjustments were made to reduce the speed regulation to below 2 per cent. Quite satisfactory operation is now obtained under this latter condition.

FIG. 5—TWO 720-HP., AND TWO 600-HP. D-C. MOTORS DRIVING THE FINISHING STANDS OF A 10-IN. TANDEM HOT STRIP MILL AT LACLEDE STEEL COMPANY

The series exciter set for indirect compounding of the two 720-hp. motors is shown between these motors

If we analyze the case of a mill consisting of two or more multi-stand sections each driven by a motor of poor speed regulation, the loop formed between sections may be much longer than in the case just considered. Referring to Fig. 6, stands 1, 2, 3, and 4 are driven by one motor while stands 5, 6, 7, and 8 are driven by a second motor. Assume again that billets are of such length that one piece may be in all stands simultaneously. Now in order to avoid stretching of the steel, it is necessary that the delivery speed of stand 4, with steel in stands 1, 2, 3, and 4, be equal to or greater than the take-up speed of stand 5, when steel is in only stand 5 of the second section. But, as the steel enters stands 6, 7, and 8, the speed of the second motor is reduced, and the take-up speed of stand 5 is lower than the delivery speed of the preceding stand. A loop is thus formed. Also as the tail end of the piece leaves stands 1, 2, and 3, the speed of the first motor increases, and the delivery speed of stand 4 exceeds the take-up speed of stand 5 by a still greater amount, so that the rate of loop growth is accelerated.

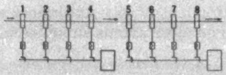

FIG. 6—EXAMPLE OF MILL CONSISTING OF TWO MULTI-STAND SECTIONS IN TANDEM, TO ILLUSTRATE LOOPING OF STEEL BETWEEN SECTIONS CAUSED BY SPEED REGULATION OF DRIVING MOTORS

It is to be noted that in the case of the mill shown by Fig. 4, the total length of excess material caused by the increased speed of the roughing mill due to decreased load as the steel leaves the early passes, is independent of the length of billets being rolled, and depends only on the speed regulation of the motor and on the layout

TABLE I

SHOWING LOOP FORMED BETWEEN STANDS 6 AND 7 OF MILL SHOWN IN FIGURE 4, WHEN 1500-HP. ROUGHING MILL MOTOR HAS SPEED REGULATION OF 5 PER CENT. CALCULATION BASED ON ASSUMPTION THAT DELIVERY SPEED OF STAND 6 WITH STEEL IN ALL ROUGHING STANDS IS EQUAL TO TAKE-UP SPEED OF STAND 7

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1. Pass number | 1 | 2 | 3 | 4 | 5 | 6 | |
| 2. Roll diameter, in | 12 | 12 | 12 | 12 | 11 | 10 | |
| 3. Roll rev. per min. at friction load | 42 | 60 | 81 | 120 | 165 | 265 | |
| 4. Cross section of steel after pass, sq. in. 7.50 | 4.45 | 3.13 | 2.32 | 1.57 | 1.24 | .85 | |
| 5. Distance to next stand, in | 40.25 | 44.50 | 40.25 | 345.00 | 304.50 | 130.00 | |
| 6. Volume of steel to next stand, cu. in | 179 | 139 | 93 | 541 | 378 | 110 | |
| 7. Motor load with preceding stands empty, hp. | 1900 | 1600 | 1300 | 1000 | 700 | 400 | 100 |
| 8. Delivery speed of stand 6 with preceding stands empty, in. per sec | 130.2 | 131.6 | 133.0 | 134.4 | 135.8 | 137.2 | 138.6 |
| 9. Volume delivered from stand 6 with preceding stands empty, cu. in. per sec | 110.7 | 111.9 | 113.1 | 114.3 | 115.5 | 116.7 | 117.9 |
| 10. Interval from time piece leaves preceding stand until it leaves this stand, sec | | 1.60 | 1.23 | .81 | 4.69 | 3.25 | |
| 11. Rate of overfeed from stand 6 during interval (10), in. per sec | | 1.4 | 2.8 | 4.2 | 5.6 | 7.0 | |
| 12. Amount of overfeed, in | | 2.24 | 3.44 | 3.40 | 26.20 | 22.75 | |
| 13. Total accumulated excess strip between stands 6 and 7, in | | 2.24 | 5.68 | 9.08 | 35.28 | 58.03 | |
| 14. Take-up speed of stand 7, in. per sec | 110.7 | 110.7 | 110.7 | 110.7 | 110.7 | 110.7 | |

of the mill. However, in the case of the mill shown by Fig. 6, there is a continuous overfeed as soon as the steel enters the second section of the mill. The loop steadily increases and the total length of excess material is directly proportional to the length of billets being rolled.

From the foregoing, it is seen that the speed regulation of motors on individual stands need not be excessively close. On motors driving several stands, good speed regulation is of relatively more importance. However, such drives are usually applied on the roughing stands where the length of piece is comparatively short and rolling speeds low so that loops are more easily taken care of. On most mills, the author believes that motors with as much as much as 4 or 5 per cent speed regulation will operate successfully, although certain types of mills may require motors of 2 per cent or less regulation.

D-c. motors are ideally suited to the drive of such tandem mills. Speed ranges of 2:1 or greater can be secured by shunt field adjustment. The number of speed points is limited only by the design of the field rheostats, and by the use of coarse and fine adjustment rheostats, each having 100 or 120 points, the total number of settings may be 1000 or more. The inherent speed regulation of shunt or lightly compounded motors can usually be kept within 3 or 4 per cent, over a speed range of 2:1, and by the addition of simple auxiliary equipment the regulation can be maintained as low as 1 per cent.

Compensating pole face windings are used to minimize the effects of armature reaction and thus make the speed drop proportional to the load. The speed curve of a shunt wound machine is usually slightly rising with load, so that a light series field is necessary to produce a flat or slightly drooping characteristic. The amount of series excitation required at full field speed with maximum shunt field excitation is different from that required with weakened shunt field. Therefore, to maintain good speed regulation over the entire speed range, it is necessary to vary the series excitation. On some machines this was accomplished by means of series field shunts and one or more switches to cut the shunts in or out of circuit.

More recently, the series excitation is furnished by a "series exciter," which is excited by the motor armature current, thus giving the same effect as a series winding on the motor itself. A rheostat in this excitation circuit is mechanically coupled to the main shunt field rheostat. Both rheostats are thus operated together and resistance values are so proportioned that the proper compounding is secured for each speed setting. Table II shows the almost negligible speed changes from no-load to double load of a 2500-hp. 160/320-rev. per min., 600-volt motor. Six of these motors are used to drive the intermediate and finishing stands of a modern continuous mill recently placed in service in the Chicago district. The first such indirectly compounded equipment was placed in service in November 1926, and there are now installed or building 46 motors totaling over 60,000 hp., to be used on eleven different mills.

TABLE II

SPEED REGULATION OF 2500 HP., 160/320 R. P. M., 600 VOLT, 3360 AMPERE, INDIRECTLY COMPOUNDED, DIRECT-CURRENT MOTOR

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| Armature amperes | Bus volts | Shunt field amperes | R. P. M. |
| 100 | 600 | 35.8 | 160 |
| 1680 | 600 | 35.8 | 160 |
| 3360 | 600 | 35.8 | 160 |
| 5040 | 600 | 35.8 | 160 |
| 6720 | 600 | 35.8 | 159 |
| 120 | 600 | 19.2 | 210 |
| 1680 | 600 | 19.2 | 210 |
| 3360 | 600 | 19.2 | 210 |
| 5040 | 600 | 19.2 | 210 |
| 6720 | 600 | 19.2 | 210 |
| 140 | 600 | 14.0 | 265 |
| 1680 | 600 | 14.0 | 265 |
| 3360 | 600 | 14.0 | 265 |
| 5040 | 600 | 14.0 | 264 |
| 6720 | 600 | 14.0 | 264 |
| 180 | 600 | 10.8 | 320 |
| 1680 | 600 | 10.8 | 320 |
| 3360 | 600 | 10.8 | 320 |
| 5040 | 600 | 10.8 | 320 |
| 6720 | 600 | 10.8 | 319 |

Alternating current adjustable speed motors may be made to have a speed regulation sufficiently low for the successful operation of some tandem mills, and there is a number of mills so driven. However, most tandem mills require several drives, and if d-c. motors are used power can be supplied from a few large motor generator sets or rotary converters, while with a-c. drives a separate regulating machine is required for each motor. Under such conditions, the total cost of a d-c. installation may be as low as that with a-c. drives. This, with the undisputed advantages of simplicity, flexibility, and easy operation, has been responsible for the large proportion of tandem mills driven by d-c. motors.

FIG. 7—DESK FOR THE CONTROL OF EIGHT MOTORS AND THREE GENERATORS ON 10 IN. STRIP MILL

## POWER REQUIREMENTS

Tests have been made on many of the mills now in operation, so that the energy consumption and capacity of driving motors for any proposed new mill may be estimated with considerable accuracy.

Table III shows a power calculation for a thirteen

TABLE III

POWER CALCULATION FOR ROLLING 16½ IN. BY 3 IN. BY 72 IN.—1010 LB. O. H. STEEL BILLETS TO 16 IN. BY 0.062 IN. STRIP

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  | 4 × 5 |  |  |  | 5 ÷ 9 |  | Fig. 8 | 6 × 12 | 13 ÷ 10 |  | Fig. 9 |  | 1010 ×17 | 18 ÷ 10 |  |
| No. of pass | Section after pass, *W.* × *T.* in. | Area after pass, sq. in. | Differ-ence sq. in. | Length before pass, in. | Volume displaced cu. in. | Roll diam., in. | Roll r. p. m. | Roll speed, in. per sec. | Duration of pass, seconds | % Area before pass | Hp-sec. cu. in. dis-placed | Net hp-sec. | Net rolling hp. | Elon-gation | Hp-sec. per pound rolled | Differ-ence, hp-sec. | Net hp-sec. | Net rolling hp. | Average hp. |
| 0 | 16.5 ×3.0 | 49.50 |  |  |  |  |  |  |  |  |  |  |  | 1.00 | 0.0 |  |  |  |  |
| 1 | 16.0 ×3.0 | 48.00 | 1.50 | 72 | 108 | 13 | 35 | 23.8 | 3.10 | 100.0 | 2.7 | 292 | 94 | 1.03 | 0.3 | 0.3 | 303 | 98 | 96 |
| 2 | 16.2 ×2.0 | 32.40 | 15.60 | 74 | 1155 | 20 | 35 | 35.6 | 3.10 | 97.0 | 2.7 | 3,125 | 1010 | 1.53 | 3.3 | 3.0 | 3,030 | 980 | 995 |
| 3 | 16.4 ×1.0 | 16.40 | 16.00 | 110 | 1760 | 20 | 50 | 52.3 | 4.15 | 65.5 | 3.2 | 5,640 | 1355 | 3.02 | 9.5 | 6.2 | 6,260 | 1510 | 1432 |
| 4 | 16.0 ×1.0 | 16.00 | 0.40 | 217 | 87 | 13 | 95 | 64.6 | 3.45 | 33.2 | 5.0 | 435 | 126 | 3.09 | 9.9 | 0.4 | 404 | 117 | 121 |
| 5 | 16.1 ×0.625 | 10.5 | 5.95 | 223 | 1325 | 20 | 75 | 78.5 | 4.50 | 32.3 | 5.1 | 6,760 | 1500 | 4.93 | 15.0 | 5.1 | 5,050 | 1315 | 1407 |
| 6 | 16.0 ×0.625 | 10.00 | 0.05 | 354 | 18 | 18 | 53 | 49.8 | 7.15 | 20.3 | 7.4 | 133 | 19 | 4.95 | 15.1 | 0.1 | 101 | 14 | 17 |
| 7 | 16.0 ×0.312 | 5.00 | 5.00 | 356 | 1780 | 20 | 95 | 99.5 | 7.15 | 20.2 | 7.4 | 13,180 | 1840 | 9.90 | 30.0 | 14.9 | 15,050 | 2100 | 1970 |
| 8 | 16.0 ×0.210 | 3.36 | 1.64 | 712 | 1165 | 16 | 82 | 68.7 | 15.40 | 10.1 | 11.0 | 12,820 | 835 | 14.75 | 45.0 | 15.0 | 15,150 | 985 | 910 |
| 9 | 16.0 ×0.145 | 2.32 | 1.04 | 1059 | 1100 | 16 | 119 | 99.5 | 15.40 | 6.78 | 19.0 | 20,900 | 1360 | 21.35 | 69.0 | 24.0 | 24,200 | 1570 | 1465 |
| 10 | 16.0 ×0.109 | 1.75 | 0.57 | 1535 | 875 | 16 | 157 | 132 | 15.40 | 4.68 | 29.4 | 25,700 | 1670 | 28.30 | 95.0 | 26.0 | 26,300 | 1710 | 1690 |
| 11 | 16.0 ×0.083 | 1.33 | 0.42 | 2035 | 855 | 16 | 208 | 174 | 15.40 | 3.54 | 40.4 | 34,500 | 2240 | 37.25 | 133.0 | 38.0 | 38,400 | 2490 | 2365 |
| 12 | 16.0 ×0.070 | 1.12 | 0.21 | 2680 | 562 | 16 | 246 | 206 | 15.40 | 2.69 | 53.0 | 29,800 | 1940 | 44.20 | 164.0 | 31.0 | 31,300 | 2030 | 1985 |
| 13 | 16.0 ×0.062 | .99 | .13 | 3180 | 414 | 16 | 286 | 240 | 15.40 | 2.26 | 63.0 | 26,000 | 1690 | 50.00 | 190.0 | 26.0 | 26,300 | 1710 | 1700 |
|  |  |  |  | 3700 |  |  |  |  |  | 2.00 |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  | 179,285 |  |  |  |  | 191,850 |  |  |

stand mill, making three edging and ten flatting passes, for the reduction of 16½ in. by 3 in. by 72 in. billets to 16 in. by 0.062 in. strip, delivering the strip at 1200 ft. per min. Columns 1 to 10 inclusive show the details of the rolling schedule, while columns 11 to 14, and 15 to 19, show the horse power for each pass by two different methods of calculation. The last column shows the averages of the results of the two methods of calculation.

There are two general methods of calculation. One,

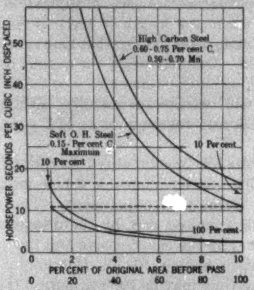

FIG. 8—ENERGY CONSUMPTION PER UNIT DISPLACEMENT CURVES FOR ROLLING 3 IN. THICK BILLETS TO STRIP ON 20-16 IN. TANDEM MILL

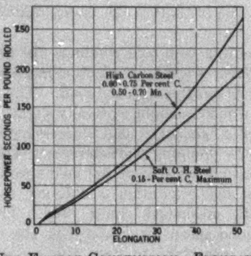

FIG. 9—NET ENERGY CONSUMPTION—ELONGATION CURVES FOR ROLLING 3 IN. THICK BILLETS TO STRIP ON A 20-16 IN. TANDEM MILL

known as the displacement method has been described in detail in a paper before the Institute by Mr. Wilfred Sykes in 1912. By this method it is assumed that during a pass there is "displaced" a volume of metal equal to the product of the length before the pass and the difference in area before and after the pass, and that the energy used is proportional to this displaced volume. The unit energy consumption is determined by test, and increases as the temperature falls and steel becomes more dense during rolling, so that curves are plotted using the percentage of the original cross section area of the billet as the other coordinate. The curves shown on Fig. 8 are plotted from the average of data from a large number of tests on a 20-16 in. strip mill, rolling 3 in. thick billets to strip varying from 0.049 in. to 0.240 in. thick. Results shown in column 14 were calculated using unit energy consumption values read from the lower curve on Fig. 8.

The other method of calculation is based on the energy required to elongate a unit volume or weight of steel, assuming the initial elongation before starting to roll as one. The curves shown in Fig. 9 are plotted from the same test data as Fig. 8, and results in column 19 are calculated from values read from the lower curve.

The results by the two methods of calculation check closely, and such calculations enable the designer to quite accurately select motor drives for a similar proposed mill, although the data must be used with care, and due regard given to the effect of variable conditions, such as mill layout, rolling speed, temperature and analysis of steel to be rolled, percentage reduction per pass, etc., any or all of which may materially influence the power requirements. For instance, the effect of the carbon content of the steel is shown by the curves, the lower curve on each of the figures showing energy consumption for "soft open hearth" steel, with carbon up to about 0.15 per cent and the upper curve showing energy consumption for rolling steel with about 0.60-75 per cent carbon, and 0.50-70 per cent manganese. The high carbon and manganese steel requires over 30 per cent more total energy to reduce to 16 gage strip than does the soft steel.

### CONCLUSIONS

The paper indicates that the tandem type of mill with individual stands separately driven by adjustable speed motors has great flexibility and is capable of rolling large tonnages, with very low labor operating costs. A-c. equipment may be used for drives, but d-c. motors are in general more simple and have better characteristics, and where several drives are installed the cost may be as low or lower than for the a-c. drives. Test data from existing mills are available, and power requirements of any proposed mill may be quite accurately estimated and correct applications of driving equipment made.

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## Discussion

**Fred Butterfield:** We have a thing that was not mentioned in the paper, namely, a split bus which helps us out on overloads on one end of the mill or the other, using two generators.

We need close regulation.—5 per cent is not satisfactory. We have had the mill up to 2300 ft. per min., delivering a piece at the finish that was sixty times as long as when it entered the furnace, and when you consider more than 2 per cent of 2300 ft., you will see what it will do with only 16 ft. between the last two stands.

Our problems are fully as much operating as they are engineering, and I do not believe this is the place to discuss them.

**L. P. Staubitz:** We happen to be one of the mills that require 2 per cent regulation. I agree with Mr. Kenyon that there are many applications where close regulation might not be so essential as it is in our particular application, but I feel that if they could produce a motor which would give absolutely flat regulation, even in mills where it is not essential, it would be better for the operating men.

Mr. Kenyon mentioned the difficulty we had, at first, with the speed. Now, that is particularly true in the finishing stands, because of the short distances we have between them.

Mr. Butterfield mentioned the split bus, and Mr. Kenyon spoke of the speed change between stands 6 and 7. We found that we were able to overcome much of this difficulty at times when we could tie the busses together. Whenever possible we attempt to carry the two busses in parallel. The motor operates from no load to full load in parallel, which was a point somewhat doubtful in our minds at the time when we were first considering the installation.

The motors of the Laclede steel plant are smaller than those of West Leechburg. That is largely due to the fact that in the Laclede plant the main mills have roller bearings, while the other mills have ordinary bearings.

We found that this mill when shut off, when it was originally driven with a-c. motors, would coast, due to these roller bearings, some 12 to 15 min. The old mills ran only about 6 or 7 min. and stopped. In steel-mill operation we often have to stop, and one of the advantages of using d-c. equipment is that, through the use of regeneration in stopping, we are able to bring this mill to a complete standstill in 45 sec.

**W. M. Ballenger:** Modern tandem or continuous mills, as designed by the mill builders, are such that a wide variety of products must be rolled. This means that the finishing stands must have reasonably good speed regulation and must operate through a comparatively wide speed range.

Since power is practically always brought to the motor room in the form of alternating current at some convenient voltage as 2200 or 6600, it is advisable to use a-c. motors wherever possible in order to get around the losses in conversion apparatus.

If the roughing and intermediate stands can be grouped into trains, large a-c. motors of the induction or synchronous types can be used to advantage. Synchronous motors are becoming more and more popular, wherever applicable, because of their ability to improve the inherent low power factor of steel mills.

On the finishing stands, because of the diversity of products to be rolled, adjustable-speed motors are practically always required. Where extremely close speed regulation is unnecessary, the speed range is not too great, and the motors required are of comparatively large size, induction motors employing either the Scherbius or Kraemer systems of speed control may be advantageously applied. Where extremely close speed regulation and a very wide range of speed are necessary, d-c. motors are almost invariably used. In instances where the adjustable-speed motors are to be relatively small it is usually better to use d-c. machines.

**A. F. Kenyon:** Mr. Butterfield has mentioned the use, at the Laclede mill, of a split bus. In this case, the supply for the five motors consists of two 1250-kw. generators, one generator supplying one bus from which is fed the 1500-hp. roughing-mill motor, and the other generator supplying a second bus which supplies the four finishing-mill motors. If desirable, the two busses can be connected together and the generators operated in parallel.

Mr. Staubitz has mentioned that the split bus enables them to increase the range of operation of their mill. There are times when it is desirable to operate the roughing-mill motor at reduced speed, which can be done by running it below 600 volts, while the finishing-mill motors are operated at the full voltage; other schedules require the opposite, full voltage on the roughing and reduced voltage on the finishing-mill motors. The split bus, undoubtedly, has added to the flexibility of this mill.

Mr. Staubitz has also pointed out that some difficulty is experienced in operating the mill with the bus split. The speeds of the motors depend not only on their inherent regulation, but also directly upon the impressed voltage. That brings up a point which I did not mention before, and which I have noted in a number of mills. The main motors are often supplied with 600-volt power from special generators, while the edging machines between the various stands of the main mill are operated from a shop supply of 250 volts. Naturally the 250-volt and the 600-volt supply sources are not tied together in any way, and considerable difficulty is experienced, due to the edging motors and the main motors changing speeds unevenly with voltage changes on either bus.

The use of roller bearings on mills is a comparatively recent development, and mills using such bearings have not been in operation a sufficient length of time to obtain any great amount of operating data. It is quite generally believed, however, that the use of such bearings will reduce the power demand of the mill to a very considerable extent.

Mr. Ballinger has mentioned that some mills can make use of a-c. drives. I agree with him perfectly, and my remarks in that connection were general only, and any proposed installation should be given individual attention before making a decision for or against any one type of drive.

# Demand Metering Equipment

## Its Application in Recent Developments

BY STANLEY STOKES[1] and LESLIE V. NELSON[1]

Member, A. I. E. E. Non-member

***Synopsis.**—Public utilities having to do with supplying electric power are continually finding themselves confronted with problems a little different from anything in the past.*

*New interconnections of superpower plants and transmission lines often present involved metering installations. The installation described herein has to do generally with such a condition and, specifically, has to provide for metering the simultaneous composite demand of an ultimate installation of 48 separate feeder circuits.*

*It is believed that this is the largest installation of its kind so far attempted. The importance of this particular job required a very exacting study of all factors and the operating results, to date, seem to bear out the solution. A novel scheme has been incorporated in the daily routine of handling the demand meter tapes. A general description of this is given. A few details of the physical installation are cited, which show the extreme care used through the whole installation.*

*While this application is specifically designed for metering, the principles involved are applicable to numerous other uses, some of which are mentioned.*

* * * * *

THE expansion of modern superpower systems through involved interconnections and remote points of metering has created situations requiring special adaptations of existing apparatus and distinct development in many of its parts. It will be the purpose of this paper to treat in detail a specific metering problem which was encountered, to giving a description of the apparatus selected and the reasons justifying this particular solution. It is felt that this solution is one which will apply to an increasing number of public utilities confronted with identical situations. At the same time it may be suggestive to others, for the apparatus has a wide use in problems dealing with time studies.

Certain electric power contracts were negotiated during 1927 whereby the entire output of the Cahokia Plant of the Union Electric Light & Power Co. of Illinois would be sold directly to three customers on a combined demand and energy basis. This required that each customer be metered for the maximum demand of his load in kilowatts and his total monthly consumption of kilowatt-hours. The maximum demand was defined as the integrated average load for that fifteen-minute interval in which the greatest total number of kilowatt-hours is taken. All three customers were to be metered in like manner.

The Union Electric Light & Power Co. is supplied entirely with its 60-cycle requirements from Cahokia by means of some 30 submarine cables, crossing under the Mississippi River and terminating in distribution substations located at various load centers throughout the city of St. Louis. The ultimate development of Cahokia provides for 48 such cables, each radiating from the generator bus through its individual oil-circuit breaker. The existing installation of 30 cables comprises three distinct capacities, *i. e.*, 3000-, 7500-, and 12,000- kv-a. per feeder.

This particular problem obviously becomes that of metering an ultimate of 48 individual circuits simultaneously, and of totalizing the demands of the different capacity cables in such a way that they will all have the correct effect upon the instruments.

The other two customers, namely, the Illinois Power & Light Corporation and the Union Electric Light & Power Co. of Illinois, are supplied by means of the new Cahokia transmitting substation, which has been constructed to step up the energy from 13,800 to 69,000 volts. A portion of the load is transmitted four and a half miles over a common line, known as the Cahokia-Venice Transmission Line, to the Venice Substation, where the Venice Power Plant is tied in and used in times of emergency for relay service. Two lines emanating from this substation, one to Alton and the other to Stallings, supply a part of the load to these two customers. A third line, extending directly from the Cahokia Substation to Belleville, supplies the remainder of the load of the Illinois Power & Light Corporation. The general arrangement of circuits is shown in Fig. 1.

Another clause in the contracts specified that all energy be metered at the generating-bus potential, that is, 13,800 volts. All meter readings must consequently be referred to a common voltage in order properly to assign transmitting and transformation losses to the individual. This necessitates high-voltage metering of the two customers' individual lines before they join into a single circuit. Both high-and low-voltage metering was installed at all points indicated on Fig. 1 without involving any special study. Readings from the high-tension meters would provide the necessary ratios for dividing the readings of the low-voltage meters registering joint use.

No attempt was made to meter these two customers at one point, for it was recognized that this method would involve more unreliable elements than by diverse metering and monthly calculations. Local factors largely decided this point. Thus the second problem was solved in a simple manner, as to meter require-

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[1] Both of the Union Electric Light & Power Co., St. Louis, Mo.

*Presented at the Regional Meeting of the A. I. E. E., St. Louis, Mo., March 7-9, 1928.*

ments. It will be touched on again, under billing procedure.

A survey of the market, for a solution of the problem of metering the 48 circuits of the Missouri Union Co., was somewhat disheartening. No simple solution was available. A study of totalizing watt-hour meters was made. It was found that these were available in capacities up to, and including, eight circuits but when applied to a 48-circuit problem they became prohibitive in cost.

Further study indicated that a simple watt-hour meter equipped with a standard device for making contacts for the pre-determined passage of a definite amount of energy would be the cheapest, and yet most reliable, solution, providing a means could be found of collecting these contacts from the watt-hour meters on the 48 circuits.

Two distinct methods seemed possible. The first scheme suggested that some means of collecting the contacts at definite regular intervals could be developed. This, in principle, would operate like an electric adding machine. The pressing of several keys would correspond to the making of contacts on several of the watt-hour meters. Periodically, the group would be totalized as one presses a totalizing key on an adding machine. The time interval between collection of contacts would have to be less than that required for the making of two successive contacts on the watt-hour meter under greatest load. Simplicity and low cost would obviously obtain with this method. This principle had the disadvantage that if a contact on a watt-hour meter should "freeze" or stick, a contact would be transmitted to the printing demand meter at each collection interval. Thus, evaluating the contacts in terms of kilowatts would give an excessive demand reading and thereby penalize the customer. It was felt that any possible chance of error or trouble in the metering device which could be guarded against should be resolved in a manner favorable to the customer and thus preserve his good will. This method, while it would incorporate novel mechanical and electrical features, had a further limitation in its inability to register all impulses when there was a large number of watt-hour meters to be totalized. This principle incorporated a piece of equipment which would be required to operate continuously and, thereby, be subject to appreciable wear. In view of these facts it was found advisable to discard this method in favor of the second, which will be described at length.

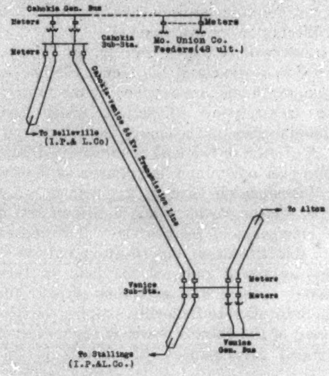
Cahokia Gen. Bus
Meters
Meters
Cahokia Sub-Sta.
Meters
Mo. Union Co. Feeders(48 ult.)
Cahokia-Venice 66 Kv. Transmission Line
To Belleville (I.P.& L.Co)
To Alton
Venice Sub-Sta.
Meters
Meters
Venice Gen. Bus
To Stallings (I.P.&L.Co.)

FIG. 1—DIAGRAM OF CUSTOMER CONNECTIONS

The second possible method provided that the contacts from the watt-hour meters be collected and recorded on a demand meter at the instant that they were made. With a multiplicity of meters, such as 48, the probabilities were that frequently several contacts on separate meters would occur simultaneously. Some means of absorbing these contacts at the instant of making and of giving them out uniformly for registration was, of course, necessary so that none would be lost in the process. This principle involved no such limitations as were encountered in the first method. Any number of circuits might be totalized by simply pyramiding the recording instruments. It also had the advantage that the recording instruments were operating only at the time that watt-hour meter contacts were made. At times of no load on the circuits there would be no wear and tear on the recording instruments.

These fundamental considerations seemed to be provided in a totalizing relay on which the manufacturer agreed to make certain necessary modifications in his standard equipment to meet our specifications adequately. By means of the instruments shown, and the schematic diagram of connections (Fig. 2), the general principle of operation may be followed. By passing an electric current through a watt-hour meter the element is made to revolve, thereby driving the contact device which makes and breaks a circuit at intervals proportional to the loading of the watt-hour meter. A contact impulse emanating from a watt-hour meter must obviously be evaluated in terms of kilowatts before it leaves the meter. This is accomplished by making the gearing and number of cam teeth within the watt-hour meter proportional to the kilowatt constant of the meter itself. After a contact has been imparted to a totalizing relay it loses its identity and value in relation to other contacts. Tracing this contact circuit (Fig. 2), we find that a coil, *A*, is energized in a totalizing relay which actuates a rocker arm and, by means of a ratchet device, *D*, advances a shaft a definite number of degrees. Simultaneous contacts on two adjacent coils (not shown) are made effective through differential gearing, *E* and *F*. A contact is then transmitted through successive stages of gearing to a coil spring between gears *H* and *K*. This spring functions to store several contacts if they occur simultaneously, and, by unwinding, revolves shafts *I* and *N* at a uniform rate, thereby giving out the same number of contacts as was received. The driven shafts are damped in their rotation by means of a disk and magnet. This final shaft, *I*, has two cams, *L*, and contact devices on it, so that its rotation is translated again into contacts which are recorded on a printing type of demand meter. Stops on the gears, *H* and *K*, on each side of the coil spring prevents over-registration of the relay. The use of double-contact devices instead of single is especially noteworthy. Each set of contacts is connected to two coils which work against each other. Once a contact is made and its coil energized, further successive contacts on this one circuit—such as is caused by chattering—have no effect until the other contact functions. This description covers the general operation of a single totalizing relay. By pyramiding these relays, as shown in Fig. 3, practically any number of circuits, or contacts, may be recorded.

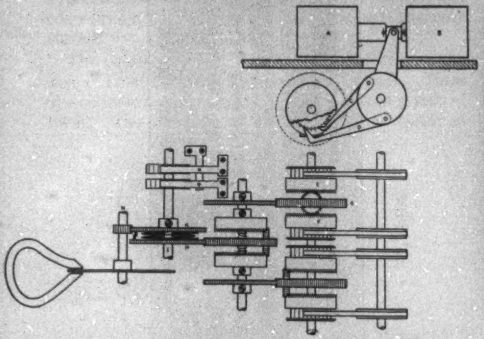

Fig. 2—Schematic Diagram of Four-Element Totalizing Relay

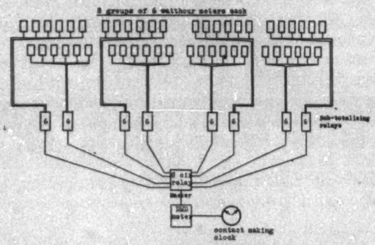

Fig. 3—Simplified Circuit Layout for 48-Circuit Totalizing Demand Meter

The 48-circuit installation comprises 8 six-circuit totalizing relays which are designated as subtotalizers. The contacts on each sub-totalizing relay are, in turn, connected to a coil on an 8-circuit totalizer, which has been designated the master totalizer. The impulses emanating from this master totalizer are recorded on a standard printometer. The 15-min. interval specified by contract for demand readings is obtained through clock-driven contacts which reset the printometer to zero reading every fifteen minutes.

Each 6-circuit totalizing relay has a contact ratio of five to one, *i. e.*, for every five impulses received, it gives out one to the 8-circuit master totalizer. The 8-circuit totalizer also has a contact ratio of five to one, giving only one contact to the recording printometer for every five received from the subtotalizers. As an example, assume that the printometer registers 150 contacts; this means that the 8-circuit relay has received 750 contacts in the 15-min. interval. On the average, each 6-circuit totalizer must have contributed 93.7 contacts and received 468.7 contacts from the 6-watthour meters connected to it. There being eight groups of watt-hour meters, a total of 3750 contacts must have been made in the watthour meters in the 15-min. interval. Each watthour meter, on the average, could have contributed 78.1 contacts per 15-min. interval, or 5.2 contacts per minute if all were evenly

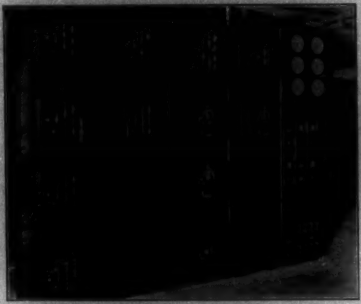

Fig. 4—Front View of 48-Circuit (Ultimate) Totalizing Demand Meter Installation,—Cahokia Plant

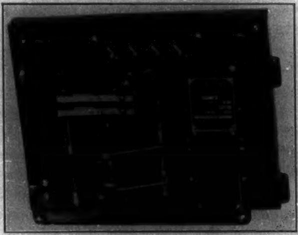

Fig. 5—Type DT-1 Two-Element Totalizing Relay, Front View with Case Removed

loaded and of the same capacity. With a permissible shaft speed on the watthour meter of 30 rev. per min. it would take slightly less than six revolutions of the watthour meter shaft to give one contact, or approximately one contact for each 12 sec. elapsed. This particular installation has a constant of 2000 kw. per contact as registered. With a maximum scheduled number of contacts of 150 this would indicate a customer demand of 300,000 kw.

It would be folly to expect perfect operation in this type of equipment in spite of the high standards of manufacture. In an attempt to guard against errors of registration it was specified that each individual totalizing relay should be equipped with a cyclometer so that the total number of impulses, received by the totalizer from the group of watthour meters connected to it, could be ascertained and checked periodically. The readings of the cyclometer dial when compared with the summation of the readings of the respective registers on the six watthour meters, connected to it, should check. Any failure of these figures to check very closely *i. e.*, within a tenth of one per cent or thereabouts, would indicate a faulty contact mechanism on one of the 6 watthour meters. Periodic checking in this matter affords a simple means of locating and correcting any such troubles before they can become accumulative. The reading of the cyclometer dial on the master totalizer, over a period of a month, will also indicate the total kilowatt-hours supplied to the customer over the 48 circuits for the entire month. This saves considerable time at the end of the month when there is always a large amount of detail reading and checking. The daily checking of the cyclometers renders this figure accurate for use.

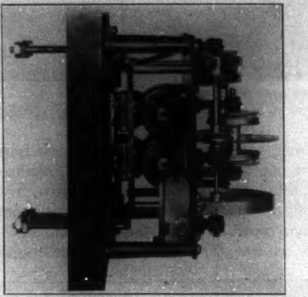

FIG. 6—TYPE DT-1 TWO-ELEMENT TOTALIZING RELAY, SIDE VIEW WITH CASE REMOVED

Meters and relays of this type, because of their inherent points of design, are fundamentally foolproof. They do not require the manufacturing precision of a delicate watch mechanism or a high-grade clock. The laboratory methods used in checking, adjusting, and calibrating these instruments assure us of a high grade solution of this particular problem. Such a metering installation, upon whose readings millions of dollars are paid out annually, must be stable and reliable to justify the confidence of all concerned.

Fig. 4 shows the front view of the installed metering panels. The wiring on the back of the panels is continuous from the contacts in the watthour meter to the coil in the totalizing relay. No joints or splices have been tolerated and, therefore, it is expected that contact troubles which ordinarily occur in small current circuits will be eliminated.

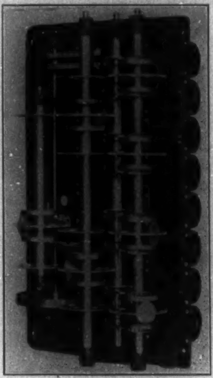

FIG. 7—TYPE DT-1 EIGHT-ELEMENT TOTALIZING RELAY FRONT VIEW OF MECHANISM, REMOVED FROM CASE

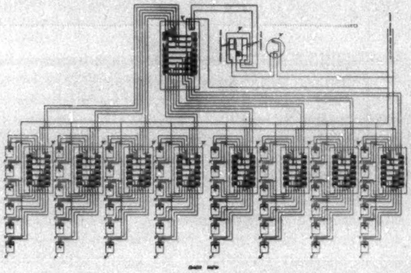

FIG. 8—WIRING DIAGRAM OF TOTALIZING RELAY SYSTEM FOR OBTAINING THE SIMULTANEOUS DEMAND ON 48 METERED CIRCUITS

Two- and four-circuit totalizing relays (Figs. 5, 6, 7) are used in similar fashion for metering the service to the Illinois Power and Light Corporation and the Union Electric Light and Power Company of Illinois. No special detail of the installation features for these two customers will be mentioned. Their problem is solved primarily by methods of computation and billing.

The contractual relations of the three customers are all predicated upon a service-at-cost arrangement. This imposes a relative value on the demand and energy usage of each customer with respect to the others. From this point of view, the distribution of losses and costs presented a unique problem which has been simply solved.

The printed records, which are taken daily from the demand meters, are in the form of narrow tapes. These are collected daily and pasted in columns on a printed form. The readings on each tape are evaluated in terms of kilowatts for each 15-min. interval. By direct reference along a horizontal line the demands of an individual customer for any particular interval may be obtained. Similarly, the demands of the other customers at this, or other, times may be obtained by selection. As was mentioned earlier, high-tension (66-kv.) metering is used for the distribution of energy where customers are served over common sources of supply. Ratios are obtained from these figures, which are used in connection with the low-tension readings, for the distribution and assignment of losses. Customer load curves may be plotted directly from the readings on these charts. At the same time, this provides a very convenient method for filing the tapes for future reference.

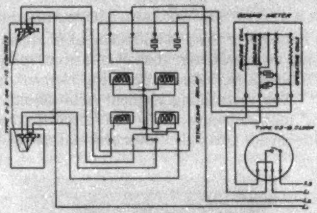

Fig. 9—Connections of Type PD Demand Meter, Type CS-9 Clock and Type Dt 2 Circuit Totalizing Relay to Measure Demand on 2 Metered Circuits. Operating Circuit 110-220 Volts, Alternating or Direct Current

The demands for equipment of this nature are, at present, quite active, and there is a certainty that these demands will increase as industrial plants grow and take energy from more than one service connection. As other power systems become interconnected simultaneous demands taken at widely separated points will be totalized. In many cases these impulses may even be transmitted over telephone lines and registered at a common point. This eliminates the necessity for synchronized clocks to assure that the same 15-min. interval is registered on all meters when located at diverse points.

The use of the totalizing relay is not necessarily confined to the summation of electrical units but, on the contrary, it may be successfully employed for numerous applications; for example, totalizing the number of street cars which pass certain points at a given interval, or for determining the operations in the manufacturing plant. It is only necessary to provide contacting devices for the specific application to open and close the required number of circuits.

The speeds of operation of the relays and demand meters are, of course, a limiting feature. But this can always be provided for, in some manner or other, through suitable gear ratios.

Wiring in this type of installation is extremely simple, as may be seen from the wiring diagram shown in Figs. 8 and 9. No long secondary leads from current transformers are necessary. All wiring which interconnects the pieces of apparatus carries only the small intermittent currents necessary to operate the relay coils. These currents are of the magnitude of milliamperes. The described installation is a composite of both d-c. and a-c. instruments operating on 60 cycles, 130 volts, and, from operating experience to date, would indicate equal reliability with either method. Any combination of d-c., 60-cycle or 25-cycle circuits may be totalized into one composite demand. This feature will, no doubt, find considerable application to customer services, where, due to changes, he finds himself confronted with the necessity of accepting both 25- and 60-cycle power from the local utility.

# The Impedance Relay
## Developments and Application

BY H. A. McLAUGHLIN[1] and E. O. ERICKSON[1]
Associate, A. I. E. E. Associate, A. I. E. E.

*Synopsis.—This paper reviews the developments made in the impedance relay since its introduction in 1923. A brief review is given of its construction and operation. Special emphasis is placed on the methods of obtaining proper potential for the restraining elements without the use of high-tension potential transformers. The use of potential from condenser type bushings is discussed. To make possible the use of low-tension potential, methods of compensating for the voltage drop through power transformers and for the shifting of the secondary neutral point have been developed. These methods are described. Some special applications of the relay are also discussed.*

* * * * *

SINCE the impedance relay was first described in an Institute paper in 1923[2] a large number of them have been applied to transmission systems both in this country and abroad. The increasing size and complexity of systems due to the many interconnections being made is responsible for the increasing use of this relay. The use of the former methods, involving over-current and directional relays, is difficult in interconnected systems having several generating stations, some of which may operate only a part of the time. In systems of this sort, the changes in direction and magnitude of the fault current may entirely ruin the selective current and time settings used with over-current and directional relays. The former protective schemes also become undesirable even on systems comparatively simple but having a number of stations in series. This is due to the fact that the relays have to be given graded time settings, which are a minimum at the end of the loop or line and which increase at each station as the generating station is approached, with the result that the most severe faults, (those occurring near the generating stations), are left on the system, sometimes for several seconds. With high standards of service to be maintained such a condition is most undesirable.

On existing systems confronted with the problem of demands for better service or the building of additional stations, considerable benefit may be derived by placing the impedance type relay at the generating station and stations nearby, without rearranging the whole protective system.

During the past few years a great many improvements in the relays have been made which have greatly widened its field of application. Some of these improvements have been described before,[3] but for the sake of completeness they will be mentioned in this paper. Much experience has been gained in the application. The difficult and important problems of obtaining the necessary potential for these relays has received a considerable amount of attention.

### CONSTRUCTION AND OPERATION

The impedance relay is quite similar in appearance to the wellknown induction disk over-current relay, except that a voltage actuated restraining element has been added. The restraining element acts directly on the contact mechanism and is connected to the over-current element through a lever arm and spring. Figs. 1 and 2 show the mechanical features of the relay. When the current in the over-current winding exceeds a predeterminal value the disk is caused to rotate. This disk is damped by a permanent magnet so that its speed is approximately proportional to the magnitude of the current. The rotation of the disk winds up the spring, one end of which is fastened to a counter-shaft geared to the disk shaft. A rocker arm pivoted at its center and mounted directly above the disk is con-

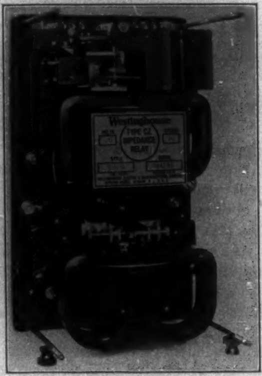

FIG. 1—IMPEDANCE RELAY SHOWING DETAILS OF CONSTRUCTION AND DIRECTIONAL ELEMENT MOUNTED IN THE LOWER PART OF THE RELAY

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[1] Both of the Westinghouse Electric and Manufacturing Company.

[2] L. N. Crichton, *The Distance Relay for Automatically Sectionalizing Electrical Networks*, A. I. E. E. TRANS., Vol. XLII, 1923, p. 527.

[3] "Developments in the Impedance Type Relay." *Electric Journal*, Feb. 1927, J. V. Breisky and H. A. McLaughlin.

*Presented at the Regional Meeting* of the A. I. E. E. *St. Louis, Mo., March 7-9, 1928.*

nected to the other end of the spring by means of a lever arm. The rocker arm has the moving contact on one end, and has suspended on the other end the core of the restraining element. The pull of the voltage coil, which opposes the closing of the contacts, is directly proportional to the applied voltage. For any given applied voltage the spring must be wound a definite amount before it will overcome the restraint and close the contacts. The speed with which the spring is wound to this definite amount, is dependent on the magnitude of the current; and since the restraint is directly proportional to the voltage, the time of operation is proportional to the impedance. Then, by properly setting the relays, selective operation may be obtained whereby the relays nearest the fault will act before any others. The time of operation also will be nearly independent of current so that this action will not depend upon the operating conditions as long as the operating point of the relay is exceeded.

In Fig. 3 is shown a family of time-current curves for various voltages.

It will be noticed that where protection against both line-to-line and line-to-ground faults is desired, it is necessary to use two relays per phase, one restrained by a delta voltage and one by a star voltage. This is necessary since either one of these voltages may be reduced to a very low value, by a fault, without reducing the other more than approximately 50 per cent. For use in special cases where space is restricted a duplex relay has been developed which combines in one unit two restraining elements operating on the same overcurrent element.

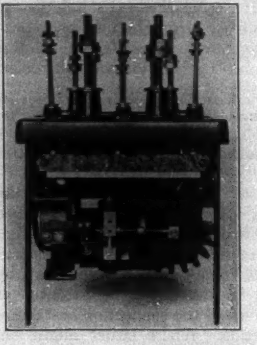

Fig. 2—Top View of Impedance Relay Showing Details of Voltage Coil and Rocker Arm

The ordinary directional element may also be combined with the impedance element to give a relay, which will operate to trip its breaker when the current flow is in a predetermined direction. This directional element is shown in the relay in Fig. 1.

### Adjustments

There are two adjustments available for setting this relay, a current and a voltage adjustment. The current taps are similar to those on the usual overcurrent induction relay. Adjustment is made by changing the position of a set screw in a connector block, thus changing the number of turns on the main coil. This fixes the minimum current at which the relay will operate and is determined mainly from a consideration of the minimum short-circuit current existent with a fault on the system. The voltage adjustment consists of inserting resistance in series with the restraining coil in order to cut down the voltage actually applied to the coil. These two adjustments used in conjunction make it possible to set the relay to operate in a short time irrespective of the impedance of the line to be protected.

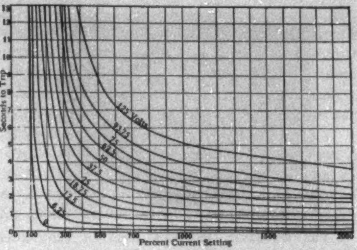

Fig. 3—Characteristic Curves of 125-Volt Impedance Relay Set on 125-Volt Tap.

These curves apply to any voltage tap, if the voltage by which the curve is designated is multiplied by $T_v/125$, where $T_v$ is the voltage tap desired

In the original relay, resistors were included in the relay case, with three voltage taps, similar to the current taps. It was soon found, however, that the range provided by these three voltage taps was insufficient, especially since the current adjustment must be made in such a way that the minimum short-circuit current gives a relay current of at least 200 per cent tap value. This requirement often necessitates the use of the four or five ampere tap, leaving it entirely to the voltage taps to obtain the proper adjustment for a line of high or low impedance.

### The External Resistor

In order to get a wide enough range of voltage taps to cover all conditions encountered, an adjustable resistance unit, known as the external resistor, was designed to be used in conjunction with the relay. The latest form of external resistor is shown in Fig. 4. By the use of this resistor and the increased number of current taps, which were made possible by the removal of the voltage taps from the relay case, very accurate settings may be obtained with lines of various lengths and a wide range of short-circuit currents.

The resistor is connected directly in series with the voltage coil of the impedance element. Fig. 5 shows a connection diagram for a simple case of line and ground protection where high-tension potential transformers are used. This diagram shows the manner in which the resistors are inserted in the restraining coil circuits.

### Directional Control

One of the most recent improvements precludes the possibility of this relay operating incorrectly on account of sudden reversals of power flow, or a surge of synchronizing power set up in a system when a faulty line is disconnected by other relays on the system. The operation of the impedance element is controlled by that of the directional element. In other words, the direction of power flow must be in the correct direction for tripping and must remain so for a sufficiently long time for the impedance element to complete its operation before it can close its contacts. Thus, it will be seen that the relay cannot be operated by sudden reversals of power such as will occur during the readjustment of a system when a fault is cleared. It will be noticed that even though these surges should be of considerable magnitude and duration, the restraining action of the impedance voltage immediately becomes predominant after the removal of a fault from the system.

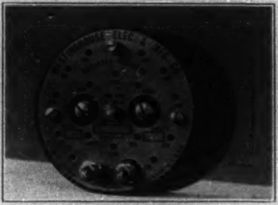

Fig. 4—The External Resistor used in Conjunction with the Impedance Relay

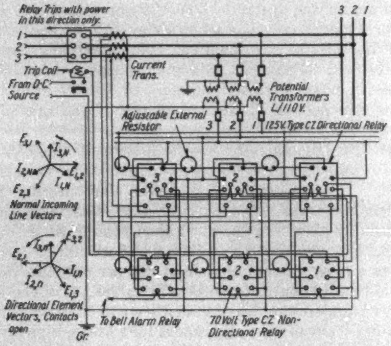
Relay Trips with power in this direction only.
1
2
3
Trip Coil
From D-C Source
Current Trans.
3 2 1
Potential Transformers L/110 V.
Adjustable External Resistor
3 2 1
125 V. Type CZ Directional Relay
$E_{3,1}$
$I_{3,N}$
$I_{2,N}$
$E_{1,2}$
$I_{1,N}$
$E_{2,3}$
Normal Incoming Line Vectors
$I_{3,n}$
$E_{3,2}$
$E_{2,1}$
$I_{1,n}$
$I_{2,n}$
$E_{1,3}$
Directional Element Vectors, Contacts open
3
2
1
3
2
1
To Bell Alarm Relay
70 Volt Type CZ Non-Directional Relay
Gr.

Fig. 5—External Connections for Line and Ground Relays on a Grounded System using High-Tension Potential Transformers

This improvement was accomplished by connecting the directional contacts in the secondary and upper-pole circuit of the impedance element current electromagnet, making it necessary for these contacts to be closed before the impedance element disk can commence to rotate. In order to make this change feasible it was necessary to redesign the secondary winding, so that a sufficiently small current and a high enough voltage would be obtained to prevent any error due to contact resistance. The fact that the directional contacts must close before the impedance element can start to function makes it possible to set them very close without danger of an incorrect operation due to rebound or jarring. How the directional control is obtained is shown in Fig. 6, the schematic diagram of a relay.

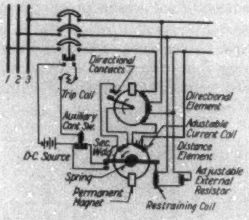
1 2 3
Directional Contacts
Trip Coil
Directional Element
Auxiliary Cont. Sw.
Adjustable Current Coil
D-C Source
Sec. Wdg.
Distance Element
Spring
Adjustable External Resistor
Permanent Magnet
Restraining Coil

Fig. 6—Schematic Diagram of Impedance Relay Showing Directional Control of Impedance Element

*Directional Element.* A new directional element embodying several improvements has been developed and will be used in this relay. It can be made to operate with either a 30 or 90 deg. relation between the current and voltage applied to the relay, by not having, or having, a resistor in the potential circuit. This allows the use of the connection best suited to the system condition. Where either might be used, it is sometimes desirable to use the 90 deg. connection with the resistor in the potential circuit, since the volt-ampere burden of this circuit is then reduced. It will be shown in a later section how desirable this is under certain conditions.

### Voltage and Current Requirements

In order that under fault conditions, the impedance measuring element at a station shall determine its tripping time according to the impedance of the intervening line between the station high-voltage bus and the fault, it is necessary that this element be supplied with the following quantities:

a. Current proportional to the line current.

b. Voltage proportional to the line voltage at the station.

1. Voltage between conductor and ground—for phase-to-ground fault protection.

2. Voltage between conductors—for interconductor fault protection.

Current transformers of the dry type, oil-insulated wound type, or bushing type satisfy the demands for current correctly representative of conductor current, and their application will not be discussed further here.

*Sources of Voltage.* At stations transmitting at generated voltage there is but one source to be considered, the transmission line itself.

At stations transmitting at other than generated voltage, and at transformer substations, there are, obviously, two main sources of voltage: (a) The high-tension bus, (b) The low-tension bus.

The use of high-tension potential transformers generally insures the delivery, to the impedance relays, of voltages correct in every respect. On very high-voltage lines, the cost of high-tension potential transformers becomes prohibitive and in such cases, other methods by which correct voltage may be obtained become economical. The direct use of low-tension potential transformers will in many cases give incorrect operation. The reasons for this will be pointed out presently.

*Potential from Condenser Bushings.* Recently a method of obtaining potential from condenser type bushings, (used in circuit-breakers and transformers), has been developed for synchronizing,[4] which also can be used on extra high-voltage systems for relaying if the volt-ampere burden is sufficiently low. This method consists, briefly, in using the condenser bushing as a potentiometer to feed a small transformer and a network consisting of a condenser and a reactor mounted directly on the breaker or transformer. In general, a voltage thus will be obtained of sufficient accuracy for relay work. Since the phase position, and not the magnitude of the voltage required for the directional element, is of importance it may be advantageous in certain cases to reduce the burden on the condenser bushings by connecting only the restraining elements to them and obtaining the directional element potential from the low-tension bus.

*Use of Potential from the Low-Tension Bus.* Under certain conditions, the potential may be taken from the low-tension bus in a transformer station and directly applied to the relay. Generally, however, as pointed out in the next sections, correct operation will not result. To take care of these cases, two systems of compensation have been developed which will allow the use of low-tension potential where this is more economical than using high-tension potential transformers. The first of these compensating schemes was suggested by several people. The second is the result of S. L. Goldsborough's work. Mr. Goldsborough also did the development work on both types.

### FAULTY OPERATION DUE TO FEEDBACK WHEN USING LOW-TENSION POTENTIAL

As an example of a possible faulty operation due to the use of low-tension potential transformers without corrective means, a system involving two generating stations $A$ and $B$ and a substation $C$, without feedback, (Fig. 7), will be considered and an interconductor fault will be assumed to have occurred close to station $B$ at the point $X$. Low-tension potential transformers are shown in use at $B$ and $C$. For simplicity high-tension potential transformers are assumed to be in use at station $A$.

Proper relaying would require the isolation of line $A\,B$ by the practically instantaneous tripping of relay No. 1, successfully differentiating with relay No. 3. This should be followed by the tripping of relay No. 4 within 0.75 sec., successfully differentiating with relay No. 5—the fault current through lines $A\,C$ and $B\,C$ having reversed upon opening No. 1 breaker.

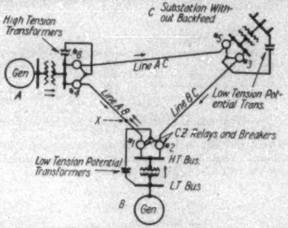
C Substation Without Backfeed
High Tension Transformers
#6
#5
#3
Line A C
Gen
A
#4
Line A B
Line B C
Low Tension Potential Trans.
X
CZ Relays and Breakers
#1
#2
HT Bus.
Low Tension Potential Transformers
LT Bus
B
Gen

FIG. 7—SYSTEM DIAGRAM USED TO DEMONSTRATE NEED OF COMPENSATION FOR FEEDBACK WHEN USING LOW-TENSION POTENTIALS

The actual relaying would, however, be as follows: Relays No. 3 and No. 4 would both trip in about 0.75 sec., but relay No. 1 would be greatly delayed, receiving as it does a voltage higher than the drop over the short section of line $A\,B$ to the fault, by an amount equal to the drop over the impedance of the power transformer at $B$—generator $B$ being responsible for the current which results in this drop. The net result is the final clearing of the fault, but only after line $B\,C$ has been opened unnecessarily.

The proper application of type KX compensators which are described later, would eliminate this incorrect operation due to the use of low-tension potential transformers.

### FAULTY OPERATION DUE TO NEUTRAL SHIFT

As an example of faulty operation due to neutral shift, a system involving a generating station $A$,

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[4] E. E. Spracklen, D. E. Marshall, and P. O. Langguth, *The Use of Condenser Type Bushings in Connection with Synchronizing Equipment*, A. I. E. E. Quarterly TRANS., Vol. 47, No. 2, April 1928, p. 684.

(Fig. 8, Part *a*), with high-tension neutral grounded and a transformer substation *B* with high-tension neutral ungrounded will be considered, and a single conductor fault-to-ground will be assumed to have occurred on conductor No. 1 close to station *B* as at the point *X*.

For the sake of simplicity, it is assumed that the fault is a perfectly solid ground and that the voltage at the generating end of the line stays up to full normal value.

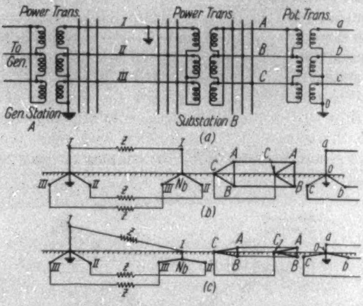

FIG. 8—SYSTEM DIAGRAM AND VECTOR DIAGRAMS.

Showing effect of shift in neutral at an ungrounded substation on a grounded system. Parts *b* and *c* show, respectively, normal vector relations and those existing for the ground fault shown in Part *a*.

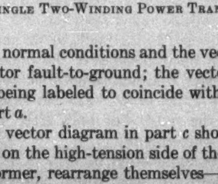

FIG. 9—ELEMENTARY DIAGRAM OF TYPE KX COMPENSATOR APPLIED TO A SINGLE TWO-WINDING POWER TRANSFORMER

In parts *b* and *c* of Fig. 8 are shown, respectively, the vectors of normal conditions and the vectors for the single conductor fault-to-ground; the vector diagrams in each case being labeled to coincide with the circuit diagram in part *a*.

The second vector diagram in part *c* shows how the star voltages, on the high-tension side of the substation power transformer, rearrange themselves—the neutral point $N_B$, being free, assumes the new equilibrant position at which the voltage $I\ N_B$ is 33.3 per cent of its initial value, or 19.3 per cent of the voltage II, III.

Although the faulted conductor is at ground potential, this shift in power transformer neutral results in a voltage *a*, *o*, instead of zero voltage, being finally made available for the voltage coil on the ground relay, resulting in delayed operation.

The type KY compensators, the application of which is outlined in a subsequent section, have been developed to compensate for this shifting of the neutral.

## TYPE KX COMPENSATOR

*Basic Principle.* In principle the type KX compensator is similar to the line-drop compensator commonly in use on feeder regulator installations. The KX compensator delivers at its two output terminals a voltage, adjustable in phase position and magnitude with respect to the current supplied to its two input terminals. By means of four dials, coarse and fine adjustment of both in-phase and quadrature voltages are made available, the dial setting being rated in volts for a primary or input current of five amperes. For the purpose of illustration a KX compensator is shown (Fig. 9) as functioning to compensate for the drop over a single two-winding power transformer.

The uncompensated voltage delivered at the instrument side of the potential transformer does not bear a constant relation to the voltage on the high-tension side of the power transformer, being higher or lower than its normal ratio depending upon the direction of power flow through the power transformer. The extent to which it deviates from its proper value is a function of the transformer impedance and of the magnitude of the current flowing through the power transformer winding.

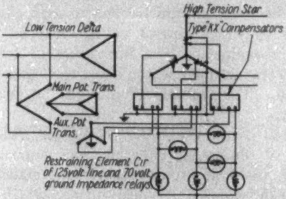

FIG. 10—CONNECTION DIAGRAM SHOWING APPLICATION OF TYPE KX COMPENSATIONS TO A STAR-DELTA CONNECTED TRANSFORMER STATION, WITH NEUTRAL GROUNDED, EMPLOYING LOW-VOLTAGE POTENTIAL TRANSFORMERS

The KX compensator is shown being supplied with current at its input terminals proportional to the power transformer current.

When the compensator dials have been set according to the resistance and reactance of the power transformer, the voltage component representing the drop over the power transformer is accounted for; and a final compensated voltage is made available, which is satisfactory for use on the impedance relay restraining element, as it bears a constant relation to the high voltages and is independent of direction of power flow.

*Typical Three-Phase Application—Two-Winding Transformers.* The application of type KX compensator to a star-delta bank of power transformers with high-tension star neutral grounded is shown in Fig. 10. Three compensators are shown, each one serving to compensate for the interwinding impedance of one transformer in the bank.

With the arrangement as shown, compensation is correct for both interconductor faults and conductor-to-ground faults, the particular relay, or relays, actively concerned with clearing the fault being supplied with voltages correctly representative of the conditions on the faulted high-tension side.

*Three-Winding Transformers.* The method of compensating for the drop through two-winding transformers shown in Fig. 10 can, of course, be expanded to care for three-winding transformers. In this case, where backfeed is possible from both the low and intermediate voltage windings, two sets of compensators and the necessary current transformers to feed them are required. The impedances used in this connection are the equivalent star impedances[5] rather than the impedances between windings, and thus special requirements are imposed on the location and ratios of the current transformers used.

*Source of Current for Compensators and Extent of Protection Resulting.* In Fig. 10 the current transformers feeding the compensators are shown located in the high-tension winding. Since the burden imposed by the compensator is too great to be handled by bushing type current transformers, these current transformers would be located in the neutral side of the power transformer windings, in order to avoid the expense of using oil-insulated current transformers in the high-tension leads. It is also possible to place the transformers on the low-tension side. In this case, to get complete compensation, it is necessary to have them inside the delta, that is, one in series with each winding. In case it is not possible to do this they may be placed in the main secondary leads and by connecting the compensators in a different manner correct compensation will be obtained for line-to-line and three-phase faults. Drops caused by circulating currents will not be compensated for and, consequently, improper compensation may result in case of ground faults which cause a circulating current to flow.

*Use of Auxiliary Potential Transformers.* In the general case the over-all potential transformer connections should be equivalent to the reverse of the power transformer connections. In Fig. 10 the power transformer is star-delta and the potential transformers are open delta plus a delta-star combination, giving a delta-star as the over-all transformation. By this means the set of star and delta voltages produced at the instrument side of the potential transformers are in phase with the particular high-tension voltages to which they are proportional.

The low side of the open-delta main potential transformer is a 125-volt delta, but is in incorrect phase position. This condition is common when standard ratio potential transformers are used. The use of a set of auxiliary transformers, preferably of a 1.73 to 1 ratio, permits the use of standard ratio main potential transformers, hence is a matter of real economy and at the same time results in proper phase positions of the final voltages. Auxiliary transformers having a 2 to 1 ratio have been used resulting in a final delta of about 100 volts; but the 1.73 to 1 ratio is preferred, on account of the fact that through the use of the 2 to 1 ratio the length of the shortest line that can be protected is somewhat increased.

In certain cases where it would be possible to get the proper voltages by the use of three main potential transformers it may be more economical still to use the main transformers connected open delta and a set of auxiliary transformers. This will, of course, depend entirely on the primary voltage of the potential transformer.

## THE KY COMPENSATOR

The KY type compensator has been designed to nullify the effect of the shift in the neutral, which takes place on the ungrounded star high-voltage side of the power transformer bank at a substation on a grounded system, thereby permitting the use of low-tension potential transformers at such stations.

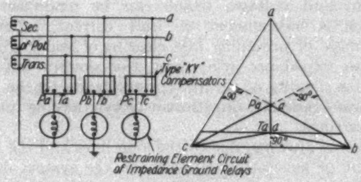

FIG. 11—PART *a*. CONNECTION DIAGRAM SHOWING APPLICATION OF TYPE KY COMPENSATORS. THIS DIAGRAM IS A CONTINUATION OF PART *a* OF FIG. 8

PART *b*. VECTOR DIAGRAM SHOWING THE UNCOMPENSATED AND THE COMPENSATED VOLTAGE VECTORS

In principle the KY compensator is similar to the KX compensator, except that it is a potential device. The KY compensator delivers at its two output terminals a voltage which for the general setting is 19.3 per cent of, and in quadrature to, the voltage impressed across its two input terminals.

When three such devices are connected, as shown in part *a* of Fig. 11, (in which the potential transformers secondaries are the same as those shown in Fig. 8 part *a*), the undesirable voltage *a*, *o* shown in the last vector diagram of part *c* of Fig. 8 (and shown on a larger scale in Fig. 11 part *b*), is completely nullified, resulting in zero voltage being delivered to the relay as is correct for the particular fault described. The voltage $P_a$, $T_a$

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[5] J. F. Peters, "Three Winding Transformers," *Electric Journal*, January 1925.

combining with the voltage $a, o$ produces voltage $T_a, o$ (zero volts) which is correctly representative of the actual faulted conductor voltage above ground at the time of the assumed dead fault-to-ground.

For ground faults which do not result in zero voltage at the point of fault it can be shown that the KY compensators still function correctly, in that the voltage delivered to the active relay bears the same ratio to the voltage it is to represent as it does under normal operating conditions. Normally, when using type KY compensators, the restraining elements of the impedance ground relays receive a voltage equal to two-thirds of the full star voltage. The fact that the above mentioned ratio is the same under all fault conditions permits correct operation to take place, the existence of the two-thirds ratio being taken into account in setting the impedance ground relays when associated with type KY compensators.

### SPECIAL APPLICATIONS

On some grounded neutral systems the current caused by an accidental ground may vary over wide ranges, due either to operating or soil conditions. The use of impedance ground relays in conjunction with a directional ground relay operating on residual current and voltage, which can be made sensitive since it is independent of load current, offers the advantage of providing fast clearing of heavy grounds by the impedance relay and the slower, but still selective clearing of the low-current faults by the more sensitive residual directional relays having graded time settings.

In some systems, due to the long lines and the small amount of generating capacity on the system during certain periods, the minimum short-circuit current may be less than the maximum full-load current. For use on such systems an impedance relay having low-current taps (used in conjunction with a fault detector), has been developed. Under normal conditions, the impedance relay is kept deenergized. On the occurrence of a fault, the fault detector makes the impedance relay operative and it tends to operate the breaker in accordance with the distance from the fault. The fault detector is responsive to an overcurrent or an undervoltage of predetermined values, all faults being accompanied by one or the other of these conditions.

### CONCLUSIONS

The impedance relay, while it is relatively new in the field of protective relays, is already being used quite extensively both in this country and abroad. Because of the impossibility of obtaining satisfactory results with overcurrent and directional relays in many cases, and the objectionable time delays involved even when selectivity can be obtained, the impedance relay is receiving more and more consideration. This is a step in the right direction since the impedance principle involves a relay independent of system conditions and dependent on direction of current flow for its operation, and on distance from the fault for its time. Many improvements and developments have been made as the result of operating experience, which also has resulted in a better understanding of its operation on the part of operating engineers, many of whom now use the impedance relay as their standard type of protection.

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## Discussion

**H. P. Sleeper:** I am interested in the *C Z* relay as being a development which I think has quite a few economic possibilities; in fact, I think the choice of the *C Z* relay for any particular system of protection is governed by the economies which it may effect.

The relay has for its principal application, in my opinion, its use on complicated systems. Unfortunately, transmission engineers of today seem to delight in complicating rather than simplifying high-tension distribution systems. Obviously, their desire is to carry the load, and they give it to you as it is and say, "Here it is, now protect it," and sometimes it is easy and sometimes it is not so easy.

Time-element directional protection has heretofore been used almost universally for networks. However, a complicated network does give rise to problems which are difficult to solve, if one desires perfect operation, namely, to open only the circuit breakers on the unit in trouble.

There are two solutions to such a problem. One is to use balanced protection between pairs of lines. This is frequently uneconomical, because it sometimes means installing lines that are not actually needed and cannot be justified on a basis of economical transmission. The other solution is to use some form of relay protection which takes care of the line by reason of faults on that line, and is not dependent on time elements in other sections of the system. The *C Z* relay does this better than any other relay that I know of that is now on the market, so for that reason I think the system economies to be afforded by the use of the *C Z* relay are very pronounced.

Now, the other problem which has been discussed by the author, namely, obtaining the correct potential for the *C Z* relay, is one that gave considerable trouble at first. It has been very ingeniously solved, and I am told by operating men who are using these relays with the low-voltage potential that they operate very successfully. We do not have any such installations on our own system.

There are, in my opinion, some very definite limitations to the application of this relay which should be carefully watched by operating engineers. For instance, the relay has sometimes been advocated for balanced protection of parallel lines. It is my opinion that the *C Z* relay here does not afford the protection possibilities that straight balanced protection affords. It is well recognized by all operating people that the time of disconnection of faults from a system should be made as short as possible. This is necessary first to relieve the bump from the system and hold synchronous apparatus in operation, and, second, to increase the inherent stability of the system, which is, of course, a most important point.

In this application, with the parallel lines available, I much prefer to use straight balanced protection. This is fundamentally due to the fact that a balanced relay can be set for a definite time. For instance, if we consider any type of balanced protection, on each end of two parallel lines, these relays may be set as fast as 0.2 or 0.1 sec. If we use 0.3 sec. as a fair time for breaker opening, the first end at least will be disconnected in, we will say, 0.2 for the relay plus 0.3 for the breaker, or 0.5 sec. total. If there was a source of feed on the other end, that end would have been disconnected simultaneously, so that in 0.5 sec. the fault would be removed from the system, which is about as fast as it can be done.

The *C Z* relay, on the same application, would have taken more nearly 0.5 sec. for relay operation, because the fastest time that a *C Z* relay can operate, in the vicinity of 300 per cent current or under, is about 0.5 sec. Add 0.3 for the breaker, and that gives 0.8 for the clearing of the fault on the one end. The other end may have cleared simultaneously, but probably would have taken more nearly 0.75 sec., which is usually assigned for its operation, so, adding 0.3 for the breaker, we get 1.05 sec., which added to the 0.8 on the other end is 1.85 sec. for the disconnection of the fault. This may be reduced possibly to the 0.8 operation on both ends simultaneously, if power is available on both ends. However, on the average location of fault and on the various connections of a system, namely, with feed-back and without feed-back on the two ends of the lines, the time will run about 30 per cent higher for a *C Z* relay to disconnect faulty parallel lines. Therefore, I prefer to use straight balanced protection. However, the *C Z* relay does afford an excellent application in connection with balanced protection, namely, as a back-up relay for the balanced relays. That is, after one line has been disconnected, the *C Z* relay can be used as a back-up for the single line that is left, and will give selective operation for that line in connection with the remainder of the system. I find this to be a most satisfactory application of these relays to balanced lines.

The matter of the potential source and using the compensators for getting the correct potential is one which must be resorted to, if high-tension potential cannot be used. I prefer not to use it, if I can avoid it, because it employs additional material that must be checked out and maintained, etc. Those who have done relay work in the field will agree with me, I think, that relay men are much like soldiers and, as "battles are won by tired men," relay connections are usually checked by tired men, on account of the hours they have to work, and so I prefer to avoid any possible complications.

A most happy solution, I believe, is the one suggested in the paper, whereby bushing potentials are used to supply the source for the restraining element of the relay and other potentials, low-tension or whatnot for the directional elements. I believe this will prove very satisfactory and good economics.

Our own system has approximately 30 such installations of standard type *C Z* relays. We had some of the original relays and ran into trouble with them because at that time they were not entirely satisfactory mechanically. However, since those have been ironed out during the past year, we have had perfect operation on our *C Z* relays.

The factor of safety on the setting of *C Z* relays is very large indeed, both over the ranges of connected capacity and over the ranges of incorrect calculation or errors in calculation. We are setting our relays with a rather high factor of safety and, as I stated, we have had no incorrect operations due to incorrect selection.

I think the *C Z* relay has a very definite field; I think it has come to stay; I think it has very definite applications and also very definite limitations. I foresee for it a future which can be compared with that of other relays which today are known as standard types.

In conclusion, I should like to ask the author two questions: First, is there anything that can be done to speed up the zero-voltage operation of the relay, which I feel should be faster than it is now? Second, is any trouble to be anticipated by the additional time element which is introduced by the interlocking of the directional element with the operating element?

**O. C. Traver:** When the original *C Z* paper was presented by Mr. Crichton about five years ago in Pittsburgh, I expressed the opinion that the general principle was sound. I still believe this, although I have some reservations when it comes to widespread application.

The impedance principle is beautifully simple from a single-phase standpoint and we become, perhaps, a bit over-enthusiastic as to our expectations of what can be done with the relay system. The author has not evaded this issue, but has brought to our attention the number of relay elements which may be required. If I understand the paper correctly, in order to secure complete and proper protection with the impedance scheme, sixteen elements are specified for one end of one three-phase line. This may be justified in certain instances, but I cannot think that the recommendation is intended to be general.

In a paper presented recently at Chicago by Messrs. Crichton and Graves, the power type of ground relay was recommended in preference to the three extra *C Z* relays. In view of the experience, for instance, as told by Roy Wilkins last September at the Del Monte Convention (where he reported that out of 1500 operations there has been no indication of faulty operation), the record seems excellent for the simple residual-power relay. If such a record can be maintained, certainly the simplicity of the one time-power relay commends itself in preference to the use of the three extra impedance relays.

A complicated network as mentioned in the paper, becomes more difficult to protect with definite time. But if inverse-time relays are used on a system having many feeds, more circuits can be relayed with a less maximum delay. The inverse-time relay requires greater thought than the definite time relay in its application, but it seems clear that the impedance relay requires even more in spite of Mr. Sleeper's suggestion that you could not set it wrong. I think in looking over the instruction book, for instance, which gives a page or two of information as to how to set it, and many tables in order to arrive at the right setting, there must be something to the problem.

The use of a small number of impedance relays on certain parts of a system otherwise protected by straight overcurrent relays will require very careful analysis before application. The impedance relay works correctly, as has been said, at the generating end, but I feel certain that for many resistance faults, the time may be higher than if straight overcurrent relays are used throughout. In fact, if impedance relays are applied at the power-station end, time probably can be saved by using the overcurrent relay also in addition, taking the time of whichever one is the more rapid.

The curves shown in the paper are not, to my mind, independent in time with respect to the current flowing; in fact, they have a tendency to rise with the increasing current above a certain value. That tendency to rise, it seems to me, is incorrect. It is obviously wrong, if you have current twenty times the setting of the relay to allow it to take half a second or a second longer time to operate than if you had three or four times normal. It means that one must set the relays higher on the average over the entire system on that account; therefore, if brought down to definite time action, the operation would be more prompt.

The question of "locking" relays has been brought up by Mr. Sleeper. Although we have with good results, long made use of the idea of requiring operation of the directional relay first before permitting the overcurrent relay to start, it is not the ideal, because of the variable time that the directional relay adds to the over-all operation of the combination. If a three-phase fault happens to be very close, by chance, and the voltage therefore low, and if the directional relay accordingly takes a fraction of a second, say a quarter of a second as a distinct possibility, that quarter of a second must be added to the total time. We are, therefore, adding a variable which is going to increase the over-all and although it may be the better of the two evils, still, it is something that needs elimination.

The new type of directional element referred to in the paper mentions only one feature, and that is the method of connection to the line. We have used this 90 deg. connection at Schenectady for over ten years, and we like it. We feel sure that the *C Z* will profit by that same connection. The alternative 30-deg. connection has also been used to advantage in a few instances.

**W. W. Edson:** (communicated after adjournment) On incoming lines with large leading power factors or on outgoing lines directional elements will normally be closed. In case of a fault ahead of the station will the directional contacts drift open before the current contacts close? In other words, has this new directional control circuit helped this condition?

At the bottom of the third page it is stated that the use of a resistor in the potential circuit of the directional elements will be discussed in a later section, but I do not see this subsequent reference. This is probably applicable to the use of condenser bushings.

Special caution should be given for the use of low-tension potential transformers where there are high- or low-tension transformer circuit breakers which might separate the potential transformers from the lines they are protecting. Also the equipment becomes quite complicated if there are two or more transformers operating in parallel as the per cent inductive drop to be compensated for varies with the number of units in service.

For sandy or rocky localities having high ground resistance, the $K X$ compensators in Fig. 10 may not be applicable as the voltage vectors might take positions similar to those for an ungrounded neutral system.

**H. A. McLaughlin:** In closing, we agree with Mr. Sleeper very heartily, that the impedance relay has limitations, and we feel that, in applying it, great care should be used in recognizing these limitations. We also agree with them that the balanced protection, from a purely theoretical point of view, is by far better than anything else, because of the very short times that are involved.

As pointed out by him, the difficulty with the balanced protection is for the single-line operations, and in that case the impedance relay offers a very nice solution for a back-up protection. If it would be possible economically to justify putting lines in pairs, and only operating them in pairs, the balanced protection would certainly be the one to use.

I want to answer the two questions of Mr. Sleeper in regard to the zero time. That zero time is now at the minimum that we have been able to get, and that is 0.25 sec. for this zero voltage, and 200 per cent current. Now, as current goes up with zero voltage, that time will be reduced considerably.

In regard to the time delay introduced by the directional element, I did not point out that the voltage used on the directional element and the voltage used on the impedance element are not the same ones, so that, for a line-to-line fault, the voltage on the impedance element will never be reduced to less than line-to-ground value and, likewise, for a ground fault, the voltage on the directional element is a different one from the one on the restraining element, and there again, it would never be reduced to less than line-to-ground voltage.

Under those conditions, we have found that the additional time involved is something of the nature of two to three cycles, and is constant over the range of operation. In other words, the voltage is sufficiently high that variations in current do not make any appreciable variation, it is simply a constant addition of between two and three cycles.

In regard to Mr. Traver's remarks, the number of elements is perhaps higher than if straight overload relays are used. However, the only reason for using impedance relays is that you cannot always get the result you want with the other relay, and for that reason you have to justify some further complications in the system. If you could not justify them, if you could get the results you wanted with the simple system, the simple system would be the one to use.

In regard to inverse-time relays, there you introduce a variable that will have a very definite effect on the time of operation of the relays, whereas with the impedance relay the fault may vary over a considerable range without greatly affecting the time of operation of the various relays.

That brings up another point that Mr. Traver mentioned, that is the fact that, from the curves, he did not think that the time was constant and independent of current. If you look at these curves and take, for instance, 300 per cent current and 6¼ volts, you will find that is approximately 0.75 sec.; then going on and taking 600 per cent current, that is double the current and double the voltage, you will find that the time is very nearly the same, it might be a fraction of a second higher, and so on, out to practically 1000 per cent of the relay setting, the time rises a very small amount, not enough to affect the selectivity of the system to any great extent, and on very few systems, I think, is there more than a variation of 5 to 1 in the ratio of minimum and maximum short circuit, at any one point.

The matter of setting relays was mentioned by Mr. Traver. Subsequent to the publication of the instruction book that he saw, with the large number of tables, a different method of setting has been developed whereby any setting may be arrived at by the use of a simple formula and the setting obtained directly. Since that, a chart has been developed by means of which with a straight edge the setting may be arrived at without any calculations at all. The various tables are not used at the present time.

In regard to using the impedance relays in systems where other relays are already used, at the generating-station end is the only place where they will give any definite gain in result. Putting them at the generating-station end is exactly equivalent to cutting one step out of the loop. In other words, you reduce the total time by one step, and if the system then becomes large enough so that it is desirable to cut out another step it may be accomplished by putting them at the stations nearest the generating station.

In the first case mentioned by Mr. Edson where a change of direction of power flow takes place with the occurrence of a fault, the question is not merely of the directional contacts drifting open. In each case there will be a definite force tending to open or close the contacts depending on whether the fault current is flowing towards the station or away from it.

The use of the resistor in the directional element may have an advantage when potential is taken from condenser bushings since it somewhat reduces the burden.

In using low-tension potential and compensators it is only necessary to compensate for the drop of one transformer bank. As Mr. Edson points out, caution should be exercised in seeing that the switching is so arranged that one bank with compensators is always in service.

In the event of a high-resistance fault the $KY$ compensators when arranged as shown in Fig. 10 will still supply a voltage proportional to that existing in the high-tension side. The drop, however, may be so small that the relay will operate very slowly due to the high restraining voltage. In cases of this sort the current will also be considerably reduced and may not be sufficiently high to operate the relay. In this case its effect on the system will be small. Where this condition exists the system described in the first paragraph under Special Applications is recommended.

# Automatic Switching of Incoming Lines and Transformers Supplying Power to A-C. Substations

BY A. E. ANDERSON[1]
Associate, A. I. E. E.

***Synopsis.**—The early applications of automatic switching were confined principally to equipment which supplied or handled the outgoing power, such as conversion apparatus and outgoing feeders. As the field broadened and the capacity of the stations increased, it became necessary to provide for greater continuity of incoming power. In order to meet this requirement it has been customary to bring in two, and occasionally three, incoming lines.*

*It is the purpose of this paper to describe briefly some of the more common forms of this type of automatic switching. By making a few minor modifications of the schemes which are described it has been possible to control automatically a complete loop or ring system.*

*Balanced power or parallel incoming lines are quite common. Ordinarily two such lines are used, although as many as six have been contemplated. All lines are usually carrying power to the substation unless a fault has developed. When cleared of the fault, the line (or lines) is automatically replaced in service.*

*In the case of the preferred-emergency type of equipment, it is customary for one line (the preferred) to carry the substation load. The second line (emergency or standby) takes this load upon failure of the first line. The application of these units to a system usually determines the sequence of operation between the two lines. A few typical combinations are described and illustrated.*

*A brief description of automatic synchronizing and transformer switching has been included.*

## INTRODUCTION

The early application of automatic switching was confined principally to rotating machinery such as rotary converters and motor-generator sets. In the development and extension of automatic control, it was a logical step that attention should be given to the switching of a-c. incoming lines which supplied power to substations having a number of distribution feeders. These feeders were usually at 2300 volts and of the automatic reclosing type. The essential purpose of the incoming line equipment was to have two (or more) sources of power available, using one as the normal or preferred and the other as the emergency or standby.

A parallel development has been one which resulted in equipments suitable for controlling parts, if not all, of transmission systems, and load responsive switching of transformer banks. It can be seen that the field of application of this kind of equipment is very broad. This paper will be confined to the more common types.

At present a total load of over 500,000 kv-a. is being taken care of by these equipments. The voltages range from 2.3 to 132 kv., while the capacity per substation, so controlled, averages approximately 5000 kv-a., the lower limit being 1000 kv-a. and the upper is slightly in excess of 25,000 kv-a. It is felt that the application of these equipments will be greatly increased in the future. There are many substations at present that are being fed by one incoming line. Extension of the system in the future, and perhaps, in addition, the increasing importance of the load supplied by such stations may result in connecting these stations to another nearby line or lines. Again, a new or existing station may be called upon to supply a type of load where continuity of service is a primary consideration. The customary solution is to bring in another source of power through a second and sometimes a third incoming line. The use of two incoming lines for such installations is quite common. Another example of this type of equipment is in the automatic control of loop or ring systems, which, at times, require automatic synchronizing in addition to the usual control. Automatic supervisory equipment is sometimes used in conjunction with this form of control.

It is not the purpose of this paper to cover the various system protective features, since this is a subject in itself. Attention will be given to the operations performed by the automatic control from the point of the individual installation rather than the system in general. However, it might be well to point out in passing that the method used in applying protective devices to a system made up in part or in whole of automatic stations is not always the same as in the case of manual stations, even though the final result may be the same. With manual operation the next move is sometimes up to the operator. In the case of automatic operation after the protective or other relays have functioned, the remaining relays must be ready at once (if necessary) for further operation, or those which have just operated must reset automatically and be in readiness for a resumption of their former operation. This last feature requires not only a study of the resetting features of the various protective devices, but a study of the system as a whole, before and after a particular switching operation. Consequently, it may be found that different relays are used for automatic operation, although basically there may be no outstanding difference between such relays and those used for manual operation. The question of maintenance is another important factor. This feature requires greater reliability of relays used in automatic stations.

In addition to the different types of incoming lines there has been prepared a brief description of automatic synchronizing and transformer equipments. The application of these various forms of automatic switching

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[1] General Electric Co., Philadelphia, Pa.

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is given under the various headings. Six common types of automatic switching are illustrated by one-line diagrams. These substations are assumed as feeding power to outgoing distribution feeders of the automatic reclosing type. Service conditions and many other local factors usually decide what type of equipment should be used.

### BALANCED POWER OR PARALLEL INCOMING LINES

A very common form of incoming lines are the parallel or balanced power as illustrated in Fig. 1.

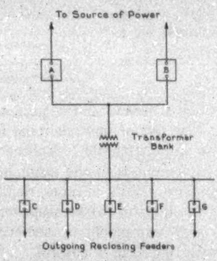

FIG. 1—ONE LINE DIAGRAM. TWO-BALANCED POWER OR PARALLEL INCOMING LINES

Normally, both *A* and *B* are closed. *A* or *B* trip on unbalanced power and reclose on voltage restoration.

This substation is fed from the same generating station by means of two lines of practically equal impedance. In case of a current unbalance as caused by a fault on one line, the oil circuit breaker feeding this line from the generating station is tripped, as well as the corresponding breaker at the substation.

The substation breakers reclose only when three-phase voltage has been established on the incoming line for a definite time. This means that the corresponding generating station breaker must be reclosed either manually or automatically and attempt to reestablish service on the line. In case of short circuit conditions, only a few such attempts are made and consequently the substation breaker does not reclose. In this manner the brunt of the overload duty is thrown on the generating station breaker. Operating experience has shown that one breaker operating on the ordinary reclosing cycle will reestablish service or lock-out and that there is little to be gained in putting a second breaker through this cycle under conditions which caused the first breaker to lock-out.

The three-phase voltage indication for a definite time shows that the fault has been removed and the line clear. The time delay is used in order to permit any protective relays to operate before the substation breaker is closed. At times it also permits certain loads to be applied gradually in a step-by-step sequence. At the expiration of this timing action the substation incoming line breaker closes and normal connections are restored.

Occasionally it is desired to use single-phase voltage on the incoming line as the indication for closing. Cases may be found where one line wire has grounded in such a way that no fault current would be obtained when the generating station breaker closed, yet due to the fact that the voltage indication was taken between the two good line wires, the incoming line breaker at the substation would reclose. Upon reclosing, a fault current would be obtained. This may be readily seen if it is assumed that the wire breaks at an insulator in such a way that the grounded end is away from the substation, and normal three-phase voltage is maintained on the substation bus by means of the other incoming line.

Therefore, due to the fact that single-phase voltage indication may result in improper reclosing action on the part of the substation breaker, it has been found advisable, when single-phase voltage indication is used, to add a relay which will permit the breaker to reclose a certain number of times in a predetermined time.

### PREFERRED-EMERGENCY INCOMING LINES FROM SYNCHRONOUS SOURCES

This type of equipment may be considered as a modification of that just described. Due to the fact that the two incoming lines, Fig. 2, are of different impedance, enough current unbalance might be obtained (to operate any protective relay) if both breakers *A* and *B* were closed for any appreciable time. In addition, any connected load on these lines may require that both lines be normally disconnected from each other. Consequently, the load at this substation is normally supplied from one line called the preferred or normal. The other line, called the emergency or stand-by, is used only in case it is in good condition and voltage

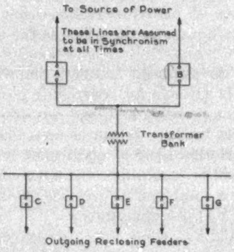
To Source of Power
These Lines are Assumed to be in Synchronism at all Times
A
B
Transformer Bank
C
D
E
F
G
Outgoing Reclosing Feeders

FIG. 2—ONE LINE DIAGRAM. TWO PREFERRED-EMERGENCY INCOMING LINES FROM SYNCHRONOUS SOURCES

Normally, either *A* or *B* is closed, and trips on voltage failure, provided voltage conditions are proper on the other (emergency) line. Restoration of voltage to the preferred line results in retransfer of the load to that line. Under certain conditions *A* and *B* may be closed simultaneously for a short interval. Either line may be made the preferred has failed on the preferred line. The choice as to which line is the preferred or emergency depends on local conditions, and can readily be made by a transfer switch.

Undervoltage releases on the oil circuit breakers are not recommended for this service. Their principal disadvantage lies in the fact that if they are instantaneous in action, they are apt to drop out on short-voltage "dips." Again, both sources may become deenergized which results in tripping a breaker when nothing is usually gained by such an operation. A subsequent return of voltage finds both breakers open and some time will be required before reconnection may be made. If time delay action is provided on the undervoltage releases, it is then found that there is a number of operating conditions that require the addition of suitable contacts. It has been found that such contacts can be placed more satisfactorily on a panel-mounted device than on an undervoltage release. These panel-mounted devices together with potential trip coils, energized from the "opposite" line, give the desired operation.

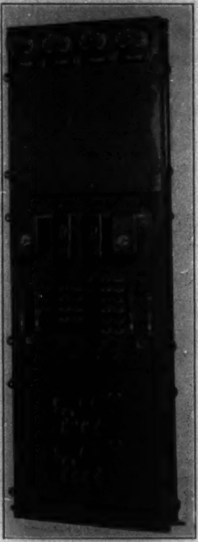

FIG. 3—PANEL-MOUNTED DEVICES FOR CONTROLLING PREFERRED-EMERGENCY INCOMING LINES FROM SYNCHRONOUS OR NON-SYNCHRONOUS SOURCES, AS WELL AS FOR CONTROLLING NON-PREFERENTIAL INCOMING LINES

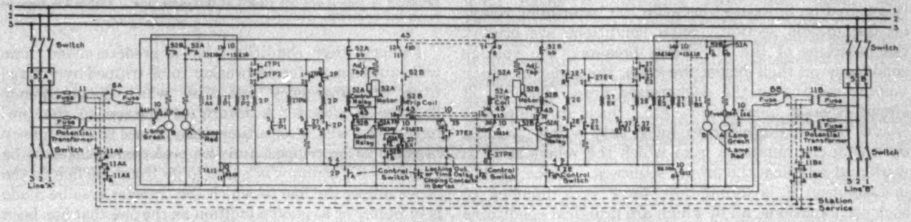

FIG. 4—ELEMENTARY DIAGRAM FOR TWO PREFERRED-EMERGENCY INCOMING LINES FROM SYNCHRONOUS SOURCES

Fig. 3 illustrates the necessary panel-mounted devices for the control of such equipment. This panel may be used for controlling a-c. or d-c. operated oil circuit breaker mechanisms. On the top section are mounted four undervoltage relays. Two relays are used for each line, one for each of the two phases. Fig. 4 gives the elementary diagram of control for two preferred-emergency lines from synchronous sources.

The general sequence of operation of such an equipment is as follows:—Assume that the preferred breaker is closed, then upon occurrence of undervoltage on any phase or phases of the preferred line, its undervoltage relays start to drop out and after a time delay will close a set of contacts. Operation from this point on depends on the condition of the emergency line. In other words its voltage conditions must be satisfactory, otherwise there is little to be gained in making a transfer. In order to make a transfer all three phases of the emergency line must be in good operating condition as determined by its respective voltage relays.

Assume conditions are thus far satisfactory for a transfer. A timing relay with a relatively longer setting is placed in action. This type of relay, as shown at the extreme left and right at the top of the middle section, Fig. 3, is energized from the emergency line, but is controlled by the undervoltage relays on the preferred line. The timing relay is used to prevent a transfer due to momentary voltage "dips" and also to allow any protective scheme (especially at the source) to operate and clear a fault which may cause such "dips" on the supply source.

At this point it might be well to state that as the result of a number of tests it has been found that the ordinary oil circuit breaker mechanism does not operate fast enough to make a successful transfer which will result in holding in all of the so-called "instantaneous" undervoltage releases commonly used with induction motor starters. At times 50 per cent of such releases have been held in, where the oil circuit breaker mechanism has been purposely speeded up. Moreover, if a group drive is used, it seems better to slow up the transfer (and bridge the usual momentary voltage "dips") and drop off all of the induction motors. This also results in less strain and longer life to the transfer equipment.

If undervoltage conditions still exist, usually from 5 to 10 sec. or over, then the preferred breaker is tripped. This tripping action is obtained by voltage from the emergency line. As soon as the preferred breaker opens the emergency breaker is closed. The control is so interlocked that when a transfer is made in this direction the preferred breaker must be open before the emergency breaker can close. The reasons for this are that a fault may exist on the preferred line and if both breakers were closed simultaneously this fault would be reflected to the emergency line, which would probably trip the breaker at the supply source and result in a loss of voltage and no means of opening the preferred breaker. Over-current protection on these equipments is usually dispensed with and potential tripping only is used in connection with the transfer operation.

Consequently in making the above transfer the load is momentarily dropped. However, if voltage remains on the emergency line and also returns to the preferred line for a definite length of time, then the preferred breaker is closed after which the emergency breaker is immediately opened. This temporary overlap is so short that protective relays will not operate, and results in a retransfer without dropping the load.

There is a number of other conditions that such an equipment has to meet. These requirements to a certain extent account for the presence of the two relays in Fig. 3, located between the two-timing relays on the middle section. Such conditions are briefly: the positions of the oil circuit breakers, the voltage conditions on their respective lines, the order in which voltage returns to the deenergized lines, type of oil circuit breaker mechanisms, etc. Such an equipment would probably appear to have only a few possible operating combinations from which the relays have to work and establish the proper sequence. Upon further investigation it is found that there is a number of such combinations, all of which are practical conditions and which can be taken care of by proper connections or choice of devices.

This type of equipment is usually furnished with two transfer switches. One is used to select the "preferred" and "emergency" sources from the two incoming lines. The other is used to enable the equipment to be operated entirely automatically or entirely manually. These two latter functions are kept independent of each other.

As mentioned above, either a-c. or d-c. operated oil circuit breaker mechanisms may be used with standard oil circuit breakers. A small number of auxiliary switches is included for interlocking purposes.

The equipment controlled by the devices as shown in Fig. 3 was used to supply power to an automatic railway substation. The two contactors on the bottom section supplied control power to the machine devices and have no direct function with the preferred-emergency unit.

## PREFERRED-EMERGENCY INCOMING LINES FROM NON-SYNCHRONOUS SOURCES

An application of incoming lines of this type is shown in Fig. 5. It will be noted that the two incoming lines are assumed to be out of synchronism at all times. Therefore, breaker *A* must be open before *B* can close, and vice versa. If this is not done, then the incoming line equipment will connect two generating stations which may be out of synchronism. Either line may be made the preferred as explained above.

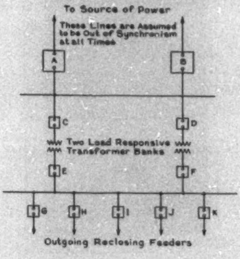
To Source of Power
These Lines are Assumed to be Out of Synchronism at all Times
A
B
C
D
Two Load Responsive Transformer Banks
E
F
G
H
I
J
K
Outgoing Reclosing Feeders

FIG. 5—ONE LINE DIAGRAM. TWO PREFERRED-EMERGENCY INCOMING LINES FROM NON-SYNCHRONOUS SOURCES

Normally, either *A* or *B* is closed, and trips on voltage failure, provided voltage conditions are proper on the other (emergency) line. Restoration of voltage to the preferred line results in a retransfer of the load to that line. Breakers *A* and *B* are not closed at the same time. Either line may be made the preferred

Undervoltage conditions for a predetermined time will cause the preferred breaker to be tripped by voltage from the emergency line after which the emergency breaker is closed. A return of voltage to the preferred line, will, after a time delay, cause the emergency breaker to be tripped and the preferred breaker to be closed. No attempt is made to go from one line to the other unless the line to which the transfer is to be made is in better or as good condition as the one that has been supplying power previously.

If both breakers are open and voltage returns to one line, the breaker on that line will close. If both breakers are open and voltage returns simultaneously to both lines, the preferred breaker will be closed.

Although it is assumed that the supply sources are usually out of synchronism, there may be cases where a tie-in between these sources may result in the two lines being in synchronism. Consequently, at such times a retransfer can be made from the emergency to the preferred line without dropping the load. Such switching can be made when proper voltage conditions exist on both lines. In order to make certain that these voltages are of the proper phase relation it is necessary to add a synchronism check relay to the customary devices. If the conditions are such that this relay does not operate then the emergency breaker must open before the preferred breaker can close. If the conditions are satisfactory, then the preferred breaker is closed, after which the emergency breaker is tripped.

With the above exceptions of sequence and application, the preferred-emergency type of incoming lines from non-synchronous sources, operate similar to those from synchronous sources.

Two load responsive transformer banks are also shown in Fig. 5. One bank carries the substation load during light load periods. The second bank is connected when the load on any one phase increases to a predetermined value. When the load on all three phases decreases to another predetermined value the second bank is disconnected.

The indication for bringing on or taking off the second bank is obtained from current transformers connected in the line. Where two or three power transformers are used it is found advisable to parallel the current transformer secondary circuits and totalize the current on each phase. This permits the use of a fewer number of master relays with a resulting simplification of relay calibrations. If one set of relays is used for each bank it becomes necessary to provide a gap in the relay calibrations, in order to avoid having two sets of relays calling for opposite switching action.

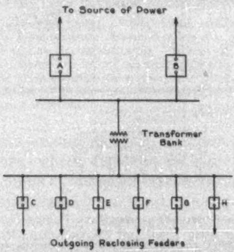

FIG. 6—ONE LINE DIAGRAM. TWO NON-PREFERENTIAL INCOMING LINES

Normally, either *A* or *B* is closed and continues to remain in this position until its voltage fails and proper voltage conditions are present on the other line. No preference is given to either line under a majority of conditions

Differential and thermal protection are ordinarily provided. Upon failure of one bank it is immediately disconnected and locked out, the remaining bank then takes its place and no further load responsive switching is performed until the lock-out relay or relays are manually reset. This enables the equipment to be inspected and the cause of failure ascertained before the unit is replaced in service. Either bank may be made the "leading" or "trailing" by means of a transfer switch.

### NON-PREFERENTIAL INCOMING LINES

At times it has been found advisable to allow either incoming line to feed the load as long as proper voltage conditions exist on its line regardless of conditions on the other line. If voltage fails on this line and conditions are satisfactory on the other, then its breaker will trip and the other close. The other line continues to feed power to the load regardless of a return of voltage to the first line. Due to the fact that a breaker can remain closed as long as voltage remains on its line and no preference is given under a majority of conditions, such forms of incoming lines are called "non-preferential." No transfer switch is necessary in order to establish preference. A certain amount of preference is obtained by the relays in order to take care of cases where both breakers are open and voltage returns to both lines practically simultaneously. In order to secure positive closing action in such a case, one breaker must be given preference over the other. Fig. 6 gives a one line diagram of this type of equipment.

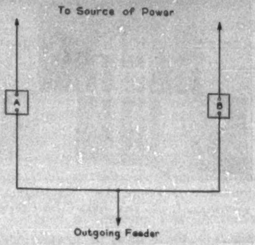

FIG. 7—ONE LINE DIAGRAM. TWO PREFERRED-EMERGENCY INCOMING LINES COMBINED WITH OUTGOING RECLOSING FEEDER

Normally, either *A* or *B* is closed and trips on voltage failure provided voltage conditions are proper on the other (emergency) line. Restoration of voltage to the preferred line results in a retransfer of the load to that line. *A* and *B* may be closed simultaneously for a short interval, depending on whether or not the two incoming lines are in synchronism. A limited number of reclosures is available in case of overload conditions

Due to the fact that one breaker is always open before the other can close, these equipments may be connected to synchronous or non-synchronous sources.

### COMBINED RECLOSING AND PREFERRED-EMERGENCY INCOMING LINES

Another common application is one in which two preferred-emergency incoming lines supply only one outgoing feeder. Overload protection is provided so as to trip whichever breaker is closed. If overload conditions persist, a certain total number of reclosures is permitted, after which the equipment is locked out. Fig. 7 illustrates the connections of such an equipment into a system. Fig. 8 illustrates an outdoor unit for such service. Such a unit is a combination of two incoming lines and one outgoing reclosing feeder.

Undervoltage conditions are taken care of in practically the same manner as the above preferred-emergency units. The combined equipment can be used for synchronous or non-synchronous sources and can also be made non-preferential.

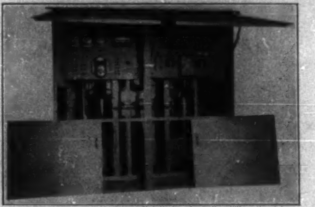

FIG. 8—COMBINED OUTDOOR A-C. RECLOSING FEEDER AND INCOMING LINES FOR 4000-VOLT CIRCUIT

## PARTIAL AUTOMATIC PREFERRED-EMERGENCY INCOMING LINES

A limited form of incoming line equipment is obtained by using one manually operated and one motor-operated breaker. The manually operated breaker is connected to the preferred line while the motor-operated breaker is connected to the emergency line.

Upon failure of voltage on the preferred line, its breaker is tripped after which the emergency breaker is closed. The equipment remains in this position until the retransfer is made manually.

A disadvantage of this type is that the emergency line may subsequently fail with its breaker closed and voltage return to the preferred source. Since the preferred breaker is manually operated it is necessary to wait for the arrival of the operator or inspector to effect the retransfer.

## AUTOMATIC SUBSTATIONS SUPPLIED BY MORE THAN TWO INCOMING LINES

Fig. 9 shows a one line diagram of an automatic station that is supplied by a number of incoming lines with their respective transformer banks. Line *A* and its associated transformer are the emergency and take the place of any line or transformers that have failed. Lines *B*, *C*, and *D* are the normal sources of power.

Normally line *D* and its associated transformer feed the low-tension bus sections which are now tied together. Whenever sufficient load demand occurs the second bank is brought on and the first bank carries only its section of the bus with its connected outgoing feeders. Continued load demand brings on the third bank with the same resulting connections. The low-tension bus is now completely sectionalized and each incoming line feeds its share of the outgoing feeders direct from the generating source. This results in radial or stub feed direct from the source to the load and also in a simple relay protective scheme.

If any line or bank fails, it is taken out of service and replaced by the emergency line. The remaining lines (in good condition) feed their share of the load direct as in the case of switching under normal conditions. The relays make the proper set up, after which the panel-mounted drum controller completes the required switching operation. The use of a drum controller for such equipment greatly decreases the number of contacts necessary on the relays and also results in a positive sequence of operation.

A total capacity of 27,000 kv-a. is handled by the automatic switching equipment in this station. The outgoing reclosing feeders in this particular installation are 2540/4400 volts using single-pole breakers with independent mechanisms and reclosing relays.

## AUTOMATIC TRANSFORMER LOAD RATIO CONTROL EQUIPMENT

Automatic switching equipment has been recently applied to transformer tap changing (under load). When two banks are used, either bank may be operated automatically or manually and when automatic may operate from individual or common master elements.

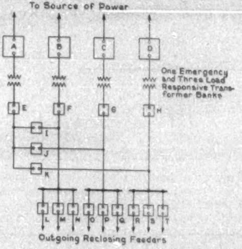
To Source of Power
A
B
C
D
One Emergency and Three Load Responsive Transformer Banks
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
Outgoing Reclosing Feeders

FIG. 9—ONE LINE DIAGRAM. THREE INCOMING LINES WITH LOAD RESPONSIVE TRANSFORMER BANKS TOGETHER WITH EMERGENCY INCOMING LINE AND TRANSFORMER BANK

Normally, *D* and *H*: *I*, *J*, and *K* are closed. As substation load is increased *C* and *G*, and *B* and *F*, are closed (successively) as required. Low tension bus is sectionalized (by opening *I*, *J*, or *K*) whenever two or more banks are operating, giving radial feed from generating station to load. As the load decreases the reverse operation takes place. On occurrence of line or transformer failures all lines and respective transformers in good condition feed their corresponding low tension bus sections, giving the above mentioned radial feed. The emergency line and bank (Breakers *A* and *E*) replace any defective line and bank

To adjust the line voltage in accordance with the changing load, the high-voltage windings have eleven taps of 2½ per cent each. To permit a change of taps without interrupting the load, a part of the high-tension winding is made in two sections, normally operating in parallel and dividing the load equally. Each of these winding halves is connected to an eleven-point ratio adjuster (Fig. 10), and the resulting circuits brought out of the transformer tank to two three-pole oil circuit breakers.

Consequently, it is possible during the tap-changing period to open circuit one section in each phase, and change the voltage tap in this open-circuited section while the other section temporarily carries the entire load of the transformer. Copper of ample cross-section and the very short transition period permits this to be done. The same change is then made in the second half. The entire change from one voltage to the next requires only 8 sec. For brief periods (less than 1½ sec.), when both breakers are closed but the two ratio adjusters are one tap apart, an internal circulating current exists, which, however, is kept within predetermined limits by sufficient inherent reactance in the transformer windings.

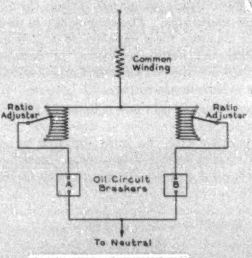

FIG. 10—ONE LINE DIAGRAM. LOAD RATIO CONTROL

Normally, *A* and *B* are closed. When voltage correction is required, as determined by suitable master element, breaker *A* is opened and corresponding ratio adjuster moves one point. Breaker *A* then closes and breaker *B* opens, followed by its corresponding ratio adjuster moving one point and in the same direction as movement of other ratio adjuster. Breaker *B* then closes. This sequence is continued as long as necessity for voltage correction is indicated

A motor-operated mechanism mounted on the transformer truck insures a properly timed operation of the internal ratio adjusters and the external circuit breakers. It is essential that the three corresponding ratio adjusters of the three phases move simultaneously from one tap to the next; therefore, these ratio adjusters are mounted together on the same shaft with full-phase insulation between them. Turning the driving shaft of this gear train one complete revolution will first change one set of three adjusters one step, then lock this set, and then turn the second set one step. Provisions are included also, so as to make certain that both sets change their taps the same amount in a predetermined time.

Contact-making voltmeters do away with any manual starting of the mechanism. If the line voltage deviates from a set value for a predetermined time, the tap-changing mechanism is automatically put in motion in one direction or the other to bring the voltage back to normal.

Two contact-making voltmeters are used on each of the two transformers, one adjusted to respond to a narrow range of voltage variations, while the other one is set for much wider differences in voltage. If the line voltage rises or drops only slightly, and if this condition persists for a predetermined length of time, the transformer will shift to the next proper tap. If, on the other hand, a considerable rise or drop occurs, the second contact-making voltmeter will respond, and will cause immediate adjustment without any time delay.

### AUTOMATIC SYNCHRONIZING OF INCOMING LINES

In general, there are two conditions under which an incoming line should be synchronized with the bus. One condition is where two sections of a system are already tied together at some other point. This means that the two voltages, at the open breaker terminals, are stationary with respect to each other, but may have a certain phase displacement due to circuit conditions.

In case two sections of a system are cut apart it will be found that the two voltages at the open breaker terminals will be rotating with respect to each other at a frequency equal to the frequency difference between the two generating sources. The equipment in the automatic substation has no control over the governors in either generating station, so that the closing operation of the breaker is determined by other factors which are: first, the frequency differential must be less than a certain value and secondly, the breaker closing impulse must be given enough ahead of synchronism so as to enable the breaker to be closed when the point of synchronism is reached, in other words, at "12 o'clock."

The calibration of the synchronzing relays for the two different operating conditions is such that one is inoperative under conditions under which the other functions.

It has been found advisable to use a separate synchronizing relay combination for each breaker. Different breakers have different closing characteristics, and even though a number of breakers could use a common synchronizing relay it has been found that the resulting scheme would be more complicated, less flexible, and more expensive than the individual control.

## Discussion

**E. L. Hough:** At the present time, there are few things that cannot be done with automatic switching equipment, and it is usually a question of proper economics in applying automatic control.

In checking over Mr. Anderson's figure of 500,000-kv-a. capacity being taken care of by incoming equipment, it would appear that this figure is low. We have in St. Louis approximately 100,000 kv-a. in automatic reclosing equipment, which are supplied by automatically switched incoming lines. I believe Kansas City has approximately the same amount.

Mr. Anderson has stated that operating experience has shown that one breaker operating on the ordinary reclosing cycle will reestablish service or lock-out. An additional point, that Mr. Anderson really did not intend to bring into this paper, which might be well worth thinking about, is the reclosing of cable circuits. Usual experience has been that after an outage on a cable, if a single reclosure does not restore service additional reclosures will not do so. It seems we should check up and find out if we would not be better off with oil circuit breakers, etc., if allowed only one closure on cable feeders.

Two different types of line-switching equipment for lines from synchronous sources are mentioned, one being the preferred-emergency equipment used where the lines are of different impedance. Where a feeder is spread out over the city to tap into other stations serving as an emergency feeder for all of them, the reason for making equipment "preferred-emergency" rather than "parallel-line" may be that it is undesirable to overload the emergency source rather than because of different line impedance.

Very frequently, the first step in the city distribution station is the use of preferred-emergency switching on two lines, and the second step would be the parallel operation of the lines. This is something that should be considered when originally designing the stations,—that is, do not design the equipment as suitable only for preferred-emergency service, but keep in mind that, some day, it may be desirable to operate the two lines in parallel.

Mr. Anderson has called attention to *load-responsive* switching of transformer banks. This is a subject that deserves further study, because there are real savings that can be made in taking transformer banks off the line at the time of light load. However we must consider the apparatus, and see that it will not be damaged by standing idle.

**Chester Lichtenberg:** Three points in Mr. Anderson's paper might be advantageously enlarged upon. On the first page appears the statement: "Consequently, it may be found that different relays are used for automatic operation."

It is a quite common occurrence to have relays applied on the basis of manual-operation experience. Then when the relays fail to function in automatic switching service, the relays are blamed rather than the application. Time and again it is found that relays in automatic stations are required to give a higher degree of service. Nobody is present to substitute for them when they do not function. They must go through their functions completely and of their own account. This hint in Mr. Anderson's paper looms large to those who have had experience in the application of manual relays to automatic station service.

We have preached for a number of years that maintenance and inspection are really the basis of successful automatic operation. Operators who are most successful with them find that a simple system of inspection and maintenance will result in a class of service equal to if not better than most manually operated stations.

The last paragraph in the paper is of even greater importance:

"It has been found advisable to use a separate synchronizing relay combination for each breaker. Different breakers have different closing characteristics, and even though a number of breakers could use a common synchronizing relay, it has been found that the resulting scheme would be more complicated, less flexible, and more expensive than the individual control."

We have tried to combine the necessary functions for each operation in one case or under cover, thereby reducing the number of devices per breaker. This emphasizes Mr. Anderson's point of a more simple system of connections.

**O. J. Rotty:** (communicated after adjournment) Mr. Anderson describes six different types of automatic switching for the supply lines to a-c. distribution substations. The most desirable type for any particular application depends upon many factors and must be determined for the individual case.

However, it is often desirable in the growth of a station or the development of a system to change the control of the incoming lines from one switching scheme to another. As a rule, this change must be made without any shutdown, and preferably without any crippling of the automatic functions. To accomplish this it is necessary to design the original scheme rather flexibly and as nearly as possible on a "unit" basis.

In the substations at St. Louis, we have adopted a design as standard which provides for two intermediate schemes of control before attaining the ultimate development. The stations are laid out initially for 7500-kv-a. capacity with two incoming lines, either one of which may be made the "preferred line," the other standing by as the "emergency line." They are from sources which may not be synchronous, but are provided with synchronism-check relays to permit tying them together on certain transfer operations. The second step in the development of the stations provides for a capacity of 11,250 kv-a. with the two lines mentioned before operating in parallel. After an interruption, either line is automatically reclosed upon the appearance of synchronous voltage.

The third and final development is for 15,000 kv-a. capacity with three incoming lines, two of which are "preferred" and operating in parallel with the third standing by as the "emergency." The control scheme is laid out so that the change from the first to the second step is carried out by the attachment of two jumpers and the removal of one 2-pole knife switch. The change from the second to the third step requires no additional apparatus nor rewiring of the two original lines and requires only the addition of the apparatus for the third or new line.

In this way it is possible to expand the station with practically no rewiring and with the least possible disturbance to normal operation.

**A. E. Anderson:** Mr. Hough seems to think that I dropped off a cipher, but I do not think I have. The value might be increased to 750,000 kv-a., or in that neighborhood.

For the protection of cable feeders, we have devised a scheme whereby the value of over-current will determine the reclosing cycle. In case the fault occurs from phase to phase, the particular maximum value of short-circuit current will place a reclosing relay in operation, which gives a certain cycle having longer time intervals than if the fault occurs from phase to ground.

This paper deals with some of the more common forms of incoming line switching. There is practically an infinite number of combinations that might be applied in service, all of which are more or less dependent on the particular conditions of the system, load, and many other factors that are more or less out of the control of the manufacturer.

I believe Mr. Lichtenberg has emphasized sufficiently the point of maintenance and characteristics of relays for automatic switching equipment. The types of equipment described in the paper are more or less flexible, some of the basic schemes—at least, we consider them basic—we can elaborate on and take care of a large number of combinations. It takes just a slight departure, here and there, in most cases, to give the desired operation.

# Improvements in Moderate Capacity Oil Circuit Breakers

BY J. B. MacNEILL[1]
Associate, A. I. E. E.

***Synopsis.***—*The increased duty requirements of power station service require circuit breaker design to give maximum interrupting capacity in a minimum of space. Compact, relatively high-power breakers having all three poles in a single round tank have been designed, which, in addition to increase in the rating for a given space, give improved performance over types previously available. The relations of the current-carrying loops inside the breaker and the diversity factor afforded by the common oil volume and air space give superior results in operation. This type of design permits use in current ranges where decreased arc energy, as compared to power handled, can be secured.*

* * * * *

THE desirability of getting increased circuit-breaking capacity in a given space arises frequently in rapidly growing power systems. There have been many cases where the oil circuit breaker has been the "neck of the bottle" in limiting power that can be handled on a switch house layout. The bus itself, disconnecting switches, and other elements may be entirely adequate to handle increased power, but the circuit breaker may present severe limitations.

It is only natural that operators and manufacturers alike should be interested in the development of an oil circuit breaker to handle a maximum power in a minimum of space. To do this, it is obvious that the combination of a three-pole breaker in a single round tank should receive consideration because of the possibilities of embodying in such a type the features that are used on high-power multiple breakers. A round tank is not in itself essential; in fact, any tank giving proper clearances and strength is sufficient. However, the ease with which necessary strength with minimum material can be obtained in a round tank with a dish bottom and a dome-shape cover, will be obvious.

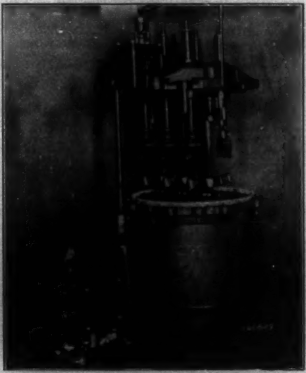

FIG. 1—THREE-POLE BREAKER IN SINGLE ROUND TANK SHOWING CONDENSER TERMINALS, CONTACTS IN OPEN POSITION, TANK REMOVED, AND ELECTRIC OPERATING MECHANISM

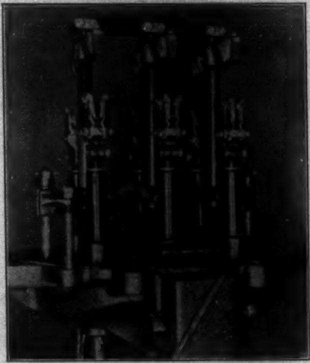

FIG. 2—THREE-POLE CIRCUIT BREAKER IN SINGLE ROUND TANK SHOWING CONTACT AND CROSS-BAR CONSTRUCTION WITH TANK REMOVED

In the past, objections have been raised in this country to the idea of multiphase switching in a single tank where considerable power is used. Many operators preferred isolation of the pole units from each other in separate cells so that in case of failure of one pole, fire and oil throw would have less chance to involve other phases. There was also the thought that when several phases were handled in a common volume of oil the chances for arcs getting together were increased. Manufacturers have, therefore, not found it generally desirable to depart from the conventional multiple single-pole arrangement for high-power work, because by so doing they would have to handle two types where one would do the work.

Recently, however, there has been an increasing

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*Presented at the Regional Meeting of the A. I. E. E., St. Louis, Mo., March 7-9, 1928.*

number of stations where space is at a premium or where cell structures have already been built and are too small to allow ordinary breakers to handle present power demands. There has also been a demand in the smaller capacities for breakers that throw minimum amounts of oil and gas and, where the outlet of the breaker can be piped away from the structure with assurance, that such oil and gas will not be released in the cell structure itself.

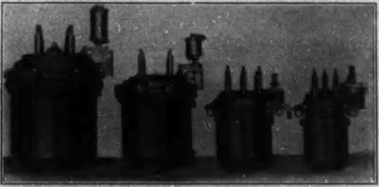

FIG. 3—FOUR SIZES OF THREE-POLE SINGLE-THROW OIL CIRCUIT BREAKERS HAVING ALL POLES IN SINGLE CYLINDRICAL TANK

The breaker shown in Figs. 1 and 2 was designed in 1922 to take care of the type of service referred to. It is a 20-in. diameter, round tank three-pole breaker embodying in a small space the general features of high-power breaker construction. The tank structure has a high ultimate strength resulting from steel construction throughout. It is equipped with a muffling device to separate the oil from the gas as it leaves the tank structure, and so arranged that the gas can be piped away—thus preventing the possibility of gas explosions in the switch cell.

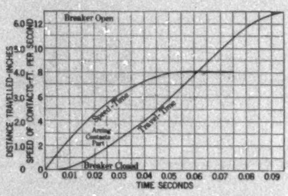

FIG. 4—SPEED OF TRAVEL CURVES OF THREE-POLE SINGLE-THROW BREAKER IN ONE ROUND TANK

The type of design shown in Figs. 1 and 2, after extensive factory and field tests on the 20-in. tank size, gave promise of extension to other capacities; and a line of circuit breakers comprising four tank sizes is shown in Fig. 3, with ratings as follows:

| Inside diameter of tank | Amperes at rated voltage | Approximate arc kv-a. |
|---|---|---|
| 16 in. | 7,500 at 7,500 volts | 100,000 |
| 20 " | 5,000 at 15,000 " | 130,000 |
| 26 " | 8,000 at 15,000 " | 200,000 |
| 32 " | 14,000 at 15,000 " | 350,000 |

The performance of a breaker depends upon two principal factors. The first of these is the amount of energy released in the structure when opening short circuits, which may be called the energy, or duty factor. The second is the ability of the structure provided to take care of this energy after it has been formed, which might be called the structure factor. The energy factor is represented by the integrated kilowatt-seconds obtained from the short-circuit current oscillograph record and the arc-voltage oscillograph record. The relationship of arc energy to short circuit kv-a. varies greatly with different designs of circuit breaker and also with different conditions of operation on the same circuit breaker structure.

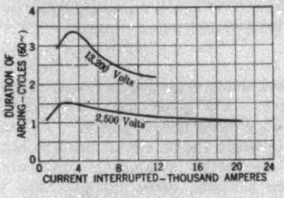

FIG. 5—CURVES SHOWING DURATION OF ARCING WITH CURRENT INTERRUPTED AT DIFFERENT VOLTAGES

A high-voltage circuit breaker handling small currents on short circuits has an entirely different ratio of arc energy to short circuit kv-a., than that of a low-voltage breaker handling high currents on short circuits. Likewise a breaker designed for, say, 15,000 volts will have a different ratio when operated at 2500 volts. A knowledge of the variations of arc energy with short circuit kv-a. is necessary to the successful design of a line of circuit breakers. This is especially so because facilities for testing the largest breakers do not exist and their design depends on extrapolating results obtained on smaller sizes.

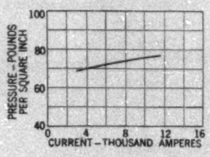

FIG. 6—TANK PRESSURE VARIATION WITH CURRENT INTERRUPTED ON THREE-PHASE, 60-CYCLE, 13,200-VOLT UNGROUNDED SHORT CIRCUITS. THREE-POLE BREAKER IN ONE ROUND TANK

Figs. 5 to 14, inclusive, show various operating characteristics of the multiple breaker in a common round tank when opening three-phase short circuits on a 60-cycle, ungrounded neutral system.

In Fig. 5 is shown the relationship between short circuit amperes and cycles of arcing at 13,200 volts and 2500 volts for a given breaker structure of the type under discussion. This is simply a curve of averages and is subject to considerable variation between successive short circuits. It serves, however, to indicate the general relationship between duration of an arc and the amount of current in the arc. The shape of this curve is affected by speed of parting of the contacts, the number of breaks in series per phase, the magnetic blow-out effect of the current-carrying loop, the spacing between the arcing contacts and the tank liners, and to some extent on the head of oil over the contacts and the volume of the air-chamber. From the point of view of the system connected to the breaker, the shape of this curve depends on the restored voltage, whether the neutral is grounded at the short circuit as well as at the machine, the power factor during the short circuit, and other considerations.

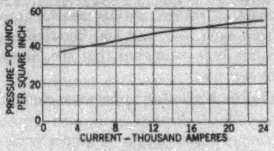

Fig. 7—Curve Similar to that in Fig. 6, for 2500-Volt Service

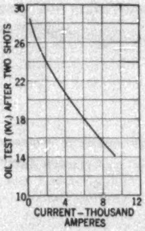

Fig. 8—Oil Test—Three-Pole Breaker in One Round Tank after Opening Three-Phase, 60-Cycle, 13,200-Volt Ungrounded Short Circuits

It has been found, however, that for 15,000 volts (and below, especially) curves of the general shape shown in Fig. 5 are secured under different conditions of system and breaker characteristics.

In Fig. 5 it is noticeable that the time of arcing for large currents is less than that with relatively small currents. The arcing time increases for a while with current, but there comes a point where this time begins to diminish rapidly, and finally the curve becomes practically asymptotic. The position of the high part of this curve depends on the magnetic blow-out action on the arcs. The type of breaker shown keeps the high point of the curve at lower current values than do some other types, because the current-carrying loops are closer together and the magnetic blow-out effects, in general, are greater. It will be obvious that a lower time of arcing at high currents results in a reduction in the arc energy dissipated in the breaker and resulting oil throw, contact depreciation, and stresses which the structure has to withstand.

Curves in Fig. 13, showing single-phase arc energy as a function of current interrupted, are of interest. For the particular case, the arc energy varies almost directly as the short circuit current but differs greatly for the different voltage classes. This is readily seen from the differences in arcing times shown in Fig. 5.

An interesting relationship is that between kilowatt-seconds dissipated in a breaker and the kv-a. of the short circuit interrupted by it. From Fig. 13 we find that for 13,200 volts the three-phase kilowatt-seconds of arc energy is 0.0035 of the three-phase short-circuit kv-a. As an illustration: at 6000 amperes the arc energy for 13,200 volts is 160 kilowatt-seconds per phase.

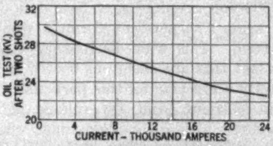

Fig. 9—Curve Similar to Fig. 8, Except for 2500-Volt Circuits

$$\text{The relation } \frac{\text{Arc energy in kilowatt-seconds}}{\text{Kv-a. interrupted}}$$

$$= \frac{3 \times 160}{13.2 \times 6000 \times \sqrt{3}} = 0.0035$$

In the same way, for 2500 volts the ratio is 0.0049. Accordingly, there is more energy lost per kv-a., in a breaker of this particular design, on low voltage, such as 2500 volts, than on 13,200 volts. With other designs of breaker this relationship may not hold, and the factors of arc energy related to kv-a. in the short may be quite different.

Several articles have been written on this general matter and it is interesting to note comparable results. Mr. P. Charpentier in the *Rev. Gén. Elec.*, May 14, 1921, developed a formula for arc energy in terms of circuit voltage, short-circuit current, and time of arcing in which he assumed that time of arcing varied directly with voltage for a given velocity of contacts. According to Charpentier's formula a breaker of this design opening 6000 amperes, three phases on a 13,200-volt circuit would have a factor of 0.0031 as the relationship between arc energy and short-circuit kv-a. This is in close agreement with the similar factor derived from the data here presented.

However, for short circuits of similar kv-a., on lower voltages this agreement does not hold. The average ratio for 2500-volt circuits (taken from data on Fig. 13) is 0.0049, while Charpentier's formula would give a ratio of 0.0006. This wide discrepancy is accounted for by the fact that arc energy as shown in Fig. 13 is rather directly a function for this particular breaker of short-circuit currents, and arc voltage at the high currents secured with low-voltage short circuits is a considerably greater proportion of line voltage than it is for higher voltage circuits. This is borne out by Figs. 10 and 11. From Fig. 10 we find that for 13,200 volts the average arc voltage at 6000 amperes is approximately 8 to 9 per cent of phase voltage, whereas for similar kv-a. at 2500 volts the average arc voltage is approximately 25 to 30 per cent, as indicated by Fig. 11.

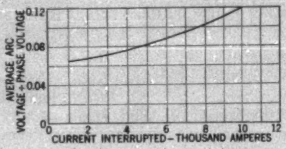

Fig. 10—Variation of Average Arc Voltage to Phase Voltage Ratio with Respect to Current Interrupted, 13,200-Volt, 60-Cycle Ungrounded Circuits

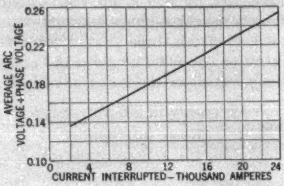

Fig. 11—Curve Similar to Fig. 10, Except for 2500-Volt Circuits

In the development of the line of breakers shown in Fig. 2 an unusual amount of short-circuit testing has been possible. In 1923 the Detroit Edison Company cooperated in the development and testing of the 20 in. tank size. At their Delray Station currents as high as 25,000 amperes at 4800 volts were handled successfully, and with much less signs of stress on the structure than on conventional forms of breakers of larger physical size. Afterward a 40,000-kv-a., 10-per cent reactance factory test plant became available, and exhaustive series of tests have been made.

It has not been possible to destroy or seriously damage the 20-in. size on the 40,000-kv-a. test set. The ability of the larger sizes, therefore, for the present must remain a matter of extrapolation. We know that the general characteristics of a small size for available test conditions is as shown in Fig. 13. The larger sizes can be tested, of course, within present power limitations. From such test data and knowledge of general characteristics it is estimated that the larger sizes are conservatively rated.

The intimate relationships between current carrying loops in this type of breaker involved recourse to certain special design features. On currents of 40,000 to 50,000 amperes it was found that ordinary, porcelain terminals would shatter under the blows imposed upon them by the reaction of the loops. It was necessary to use a terminal insulation, having mechanical strength and at the same time sufficient flexibility to prevent breakage. The condenser type terminals with heavy ground band and clamp construction, as shown in the illustrations, seemed most desirable.

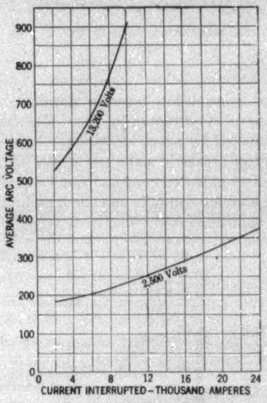

Fig. 12—Relation of Average Arc Voltage to Current Interrupted for Three-Phase, 60-Cycle Ungrounded Short Circuits. Three-Pole Breaker in One Round Tank

A similar mechanical action took place between the moving contacts at high currents. During one test made, with current rushes of 60,000 to 70,000 amperes at 4800 volts on the 20-in. tank size, the circuit was ruptured not by the opening of the breaker in the ordinary way, but by the fracture of the lifting rods causing the moving contacts to be thrown violently into the bottom of the tank. The circuit was ruptured with approximately one-half cycle of arcing on 60 cycles and represents one more of those cases where the operation was successful but the patient died. It was found desirable to strap the moving contact elements together where heavy currents at the lower voltages were involved.

The question frequently is asked whether the mechanical speed of operation of a breaker is seriously affected by the short-circuit current flowing through it. Mechanical strains on contact parts due to mechanical blow-out effects are a function of the square of the current. Fig. 14 shows the speed of operation of a breaker such as referred to with varying currents being interrupted. The general conclusion may be drawn that for small structures having close mechanical loops this effect becomes noticeable around 15,000 amperes and increases in effect fairly rapidly with current increase beyond that point.

There are certain diversity factors about this type of breaker that will interest an operating man. The oil volume and air volume are common to the three poles. Since by far the greater number of short circuits is single phase, the total oil volume will not depreciate as fast as though the single-phase short circuit had been on one-third of the oil, which would be the case with a multipole breaker having separate tanks. Also, the common air volume tends to diminish the shock to the breaker structure that occurs on single-phase short circuits, so that while the maximum pressure to which the breaker may be subjected may be considerable, yet the average pressure under operating conditions will be reduced. In general, it is felt that less maintenance for a given duty will be obtained with this form of breaker than with a multiple, single-pole breaker, and also that the maintenance is more easily and quickly performed.

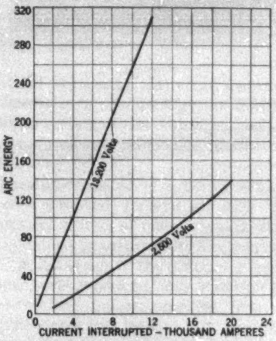

FIG. 13—RELATION OF ARC ENERGY PER PHASE TO CURRENT INTERRUPTED ON 60-CYCLE UNGROUNDED CIRCUITS. THREE-POLE BREAKER IN ONE ROUND TANK

A careful analysis of test data is necessary in formulating ratings. Actual operating conditions vary from test conditions. Over the life of a breaker operating speed may vary somewhat, the condition of the oil will change at times, and certain circuit conditions will be found much harder on a breaker than others. With a general understanding of the operating characteristics of a breaker, test data can be properly evaluated and a rating given that will be conservative and insure satisfactory operation.

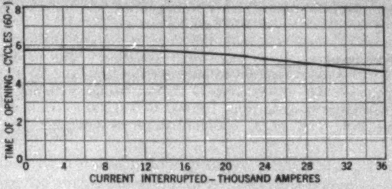

FIG. 14—RELATION OF TIME OF OPENING FROM BEGINNING OF MOVEMENT UNTIL COMPLETION OF STROKE AGAINST CURRENT INTERRUPTED. THREE-POLE BREAKER IN ONE ROUND TANK

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## Discussion

**R. R. McGee:** As Mr. MacNeill has brought out, oil circuit breakers of minimum size for moderate interrupting capacity and moderate voltage are constantly assuming greater importance. Operators are demanding breakers which are safe and reliable, and which will occupy the minimum of space and require the minimum of maintenance attention.

As a result of this increasing demand the writer's company has applied to a new round-tank breaker many of the electrical and mechanical principles of design essential to the larger breakers.

Among the design features essential to the attainment of high interrupting capacities are: the internal unit mechanism, oil-separating chambers and gas vents, round tanks with dome covers, and ample mechanical strength. All of these features are to be found in the new round-tank breaker for moderate interrupting capacity. The internal mechanism, of course, prevents contact reclosure due to unbalanced pressures acting on the mechanism; the separating chambers and gas vents provide adequate relief for the gases without permitting oil throw; and by proper design of the round tank with its dome cover ample mechanical strength is secured.

The moderate-duty breaker employs one tank for all three phases with considerable saving of space.

The top frames are dome-shaped because this construction, together with the use of a round tank, eliminates distortion. The heavy, bulky, and expensive castings formerly used have been replaced by the lighter but stronger boiler-plate construction.

The contacts of this new moderate-capacity breaker are of the wedge-and-finger construction. The stationary contact fingers are the so-called wide-angle fingers. They are self-alining, and their contact surfaces are at all times maintained parallel to the contact surfaces of the blade, thus assuring maximum contact. Extended fingers and a removable section of the blade are used to bear the brunt of the arcing, protecting the main contact surfaces. Contacts of this same type are employed in the plain-break breakers of larger size and are also used in many cases to supplement the explosion-chamber contacts.

There is a little similarity however, between the bushings which support the contacts. In the smaller breaker, designed only for moderate voltages and for indoor service, bushings of Herkolite surround the central conductor. The assembled bushings are individually removable from the frame. In the larger breakers where higher voltages are encountered, compound- or oil-filled porcelain bushings are used.

Of course there is a wide difference in the application of the several breakers which have been described. The moderate-capacity breakers referred to are built for 7500- and for 15,000-volt service, 400- to 3000-ampere current ratings, with interrupting capacities ranging from 100,000 to 250,000 kv-a., in accordance with N. E. M. A. standard steps, as determined by the selection of a 16-in. to 32-in. tank. The new line of large indoor oil circuit breakers has voltage ratings of 15,000, 25,000, or 37,000 volts, with normal currents up to 4000 amperes. Here the interrupting capacities vary from 350,000 to 2,000,000 kv-a., with tanks ranging from 16 in. to 36 in. in diameter. The round-tank breakers for outdoor service are built for all standard voltages from 15,000 to 220,000 volts, and may be obtained with either finger-and-wedge, or explosion-chamber contacts, except above 154,000 volts where explosion chambers only are used. Interrupting capacities from 350,000 to 750,000 kv-a. can be obtained from the plain-break breakers. When explosion chambers are used, interrupting capacities from 750,000 to 2,500,000 kv-a. are available. The tanks are mounted directly on the foundation for higher voltages, and with this mounting manholes are provided to afford inspection of the internal parts.

# The Vibration of Transmission-Line Conductors

BY THEODORE VARNEY[1]

Associate, A. I. E. E.

*Synopsis.—This paper is a continuation of a former one by the writer in May, 1926.*

*Records are given of vibration in actual transmission lines under widely varying conditions and with various conductor materials. These observations indicate the limiting values of wavelength frequency and amplitude of such vibrations encountered in service.*

*Laboratory experiments are described in which the observed conditions were artificially reproduced in a large conductor. The stresses adjacent to a point of support were studied with the aid of a microscope. The wave shape was plotted and the energy required to maintain vibration was recorded.*

*All conductor vibration breaks observed in practise have occurred at supports or badly made joints. The conclusion is reached that if the radius of curvature at the support can be maintained at least equal to that at the center of a loop, no breakage will occur.*

*Mathematical expressions are given for determining the radius of curvature at the center of a loop, the bending moment at a support, and the necessary additional amount of conductor stiffness at the support to satisfy the desired condition.*

*A simple form of stiffening device is described which even in a more crude form has been found effective in several cases of actual service.*

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IN the previous paper[2] the writer discussed the action of the wind on a suspended conductor and gave rules for determining the wavelength and frequency of the resulting vibrations.

Since the date of that paper, records have been kept of the wind action upon a large number of transmission lines equipped with different kinds of conductors and installed under various conditions. Typical cases selected from these data are listed in Table I.

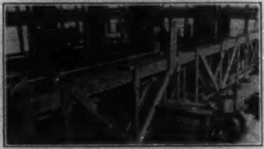

FIG. 1—FRAME FOR TESTING VIBRATION OF CONDUCTOR

Experimental apparatus was next installed at the Carnegie Institute of Technology at Pittsburgh by means of which certain of the data observed in the field could be reproduced in a particular conductor of large size.

This apparatus consisted of a heavy wooden frame provided with grooved pulleys at each end. The distance between centers of pulleys was 50 ft. and tension was maintained by turnbuckles and a dynamometer installed in the lower side of the conductor loop.

Vibrations were produced and maintained by an 1/8-hp., 110-volt d-c. motor, operated from a storage battery. The motor was located 6 ft. from one end of the span and was belted to a small counter shaft carrying a flywheel, a tachometer, and a crank disk. The latter was arranged to receive a wrist pin at varying radii, and which in turn engaged with a light wooden connecting rod and guided plunger. This plunger was connected with the conductor by means of a small spiral tension spring. The travel of the plunger was adjusted to 1½ in. when the spring tension varied from ¾ to 4 lb.

The field of the motor was separately excited and held constant. The armature speed was controlled by an adjustable resistance. The power consumed was so small that the speed of the motor could be held constant and the conductor maintained in resonant vibration continuously. By varying the speed, one, two, three, and four loops could be obtained.

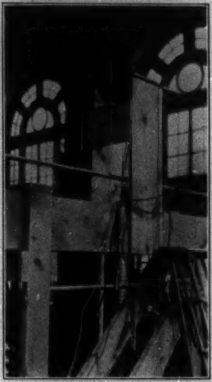

FIG. 2—SHOWING METHOD OF VIBRATING CONDUCTOR

Table II gives conductor tension, loop length, amplitude, frequency, and watts input to motor when vibrating the conductor and when disconnected. The power consumption is inconsistent as will be noted by the fact that in some cases it is less when connected than when disconnected. This is believed to indicate that the friction losses were variable and large compared to the

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[1] Aluminum Company of America, Pittsburgh, Pa.

[2] *Notes on the Vibration of Transmission-Line Conductors*, TRANS. A. I. E. E., 1926, p. 791.

*Presented at the Regional Meeting of the A. I. E. E., St. Louis, Mo., March 7-9, 1928.*

TABLE I

EFFECT OF WIND ACTION ON TRANSMISSION LINES—TYPICAL CASES

NOTE: Columns 11 to 19 are included for cases *a* to *e* at the foot of the Table

| 1 Cond. | 2 Diam. in. | 3 Weight per ft. (lb.) | 4 Span (ft.) | 5 Sag (ft.) | 6 Temp. (Fahr.) | 7 Wind (M. P. H.) | 8 Loop (ft.) | 9 Frequency (Cy. P. S.) | 10 Amp. 1/32 inch |
|---|---|---|---|---|---|---|---|---|---|
| (*a*) ACSR | 1.246 | 1.332 | 800 | 11.5 | 80 | 2.6 | 15.0 | 16.5 – | 26 |
| " | " | " | " | 11.8 | 90 | 4.1 | 20.7 | 11.0 | 6 |
| " | " | " | " | 10.9 | 64 | 4.5 | 15.0 | 15.3 | 20 |
| " | " | " | " | 11.5 | 80 | 4.6 | 14.5 | 17.5 | 8 |
| " | " | " | " | 11.4 | 78 | 5.0 | 20.1 | 9.1 | 6 |
| " | " | " | " | 11.2 | 68 | 5.5 | 20.0 | 13.1 – | 24 |
| " | " | " | " | 11.7 | 88 | 5.7 | 13.5 | 13.8 | 20 |
| " | " | " | " | 11.7 | 88 | 6.0 | 14.5 | 16.1 | 18 |
| " | " | " | " | 11.0 | 66 | 6.1 | 16.3 | 14.4 | 18 |
| " | " | " | " | 11.2 | 68 | 6.1 | 20.0 | 14.6 | 12 |
| " | " | " | " | 10.9 | 64 | 6.9 | 34.5 | 9.3 – | 18 |
| " | " | " | " | 11.0 | 66 | 7.1 | 31.0 | 7.3 | 8 |
| " | " | " | " | 10.9 | 64 | 7.3 | 33.0 | 8.4 | 20 |
| " | " | " | " | 11.8 | 90 | 9.5 | 13.5 | 15.3 | 12 |
| ACSR | 1.093 | 1.024 | 1000 | 22.7 | – 2 | 7.0 | 17.5 | 12.0 | 14 |
| " | " | " | " | 25.0 | 26 | 7.2 | 16.0 | 10.0 | 12 |
| " | " | " | " | 23.8 | – 1 | 10.0 | 14.0 | 9.2 | 6 |
| " | " | " | " | 23.8 | 10 | 10.0 | 12.0 | 10.8 | 6 |
| " | " | " | " | 24.5 | 20 | 10.0 | 11.0 | 6.4 | 4 |
| " | " | " | " | 13.9 | 20 | 2.0 | 16.5 | 8.2 | 20 |
| " | " | " | " | 13.2 | 8 | 2.6 | 25.0 | 7.3 | 24 |
| " | " | " | " | 12.3 | –22 | 4.5 | 15.0 | 7.0 | 32 |
| " | " | " | " | 13.9 | 18 | 5.5 | 25.0 | 7.7 | 6 |
| " | " | " | " | 14.0 | 14 | 6.2 | 20.0 | 11.1 | 24 |
| " | " | " | " | 14.4 | 15 | 9.0 | 14.5 | 10.3 | 24 |
| " | " | " | " | 12.9 | – 6 | 12.0 | 13.5 | 15.4 | 22 |
| " | " | " | " | 14.7 | 18 | 13.2 | 15.0 | 14.3 | 4 |
| ACSR | " | " | 921 | 20.0 | 32 | 2.8 | 24.0 | 8.5 | 28 |
| " | " | " | " | 20.0 | 30 | 2.9 | 24.0 | 10.5 | 14 |
| " | " | " | " | 19.8 | 30 | 4.7 | 16.0 | 11.4 | 16 |
| " | " | " | " | 19.8 | 30 | 4.7 | 16.0 | 11.3 | 14 |
| " | " | " | " | 19.8 | 30 | 4.7 | 16.0 | 10.7 | 22 |
| " | " | " | " | 19.6 | 24 | 5.8 | 12.0 | 11.9 | 12 |
| ACSR | " | " | 781 | 18.9 | 48 | 1.0 | 18.9 | 8.6 | 8 |
| " | " | " | " | 19.4 | 56 | 1.4 | 15.8 | 10.0 | 15 |
| " | " | " | " | 18.8 | 46 | 2.9 | 43.5 | 11.0 | 17 |
| " | " | " | " | 18.9 | 48 | 3.2 | 27.4 | 11.0 | 16 |
| (*b*) " | " | " | " | 18.9 | 48 | 3.3 | 14.3 | 9.3 | 24 |
| " | " | " | " | 18.9 | 48 | 3.4 | 20.3 | 8.5 | 6 |
| " | " | " | " | 18.7 | 44 | 4.3 | 39.0 | 7.0 | 14 |
| ACSR | 1.000 | 0.858 | 1200 | 20.2 | 78 | 3.5 | 13.0 | 19.7 | 10 |
| " | " | " | " | 20.5 | 70 | 3.9 | 21.7 | 13.0 | 28 |
| " | " | " | " | 20.5 | 70 | 5.2 | 24.5 | 10.5 | 12 |
| " | " | " | " | 20.5 | 70 | 5.6 | 24.2 | 12.0 | 20 |
| " | " | " | " | 20.5 | 70 | 8.0 | 14.7 | 20.0 | 4 |
| " | " | " | " | 18.2 | 50 | 8.0 | 18.9 | 15.0 | 24 |
| (*c*) " | " | " | " | 18.2 | 51 | 8.9 | 14.5 | 18.3 | 24 |
| " | " | " | " | 18.2 | 50 | 10.0 | 12.8 | 21.0 | 14 |
| " | " | " | " | 20.5 | 70 | 19.1 | 12.2 | 23.0 | 6 |
| " | " | " | " | 20.5 | 70 | 22.5 | 12.3 | 22.5 | 8 |
| ACSR | 1.000 | 0.858 | 984 | 13.9 | 70 | 5.0 | 15.9 | 15.9 | 8 |
| " | " | " | " | 13.9 | 70 | 5.7 | 15.6 | 13.0 | 8 |
| ACSR | 0.953 | 0.779 | 792 | 17.6 | 59 | 2.2 | 12.4 | 16.3 | 4 |
| " | " | " | " | 17.6 | 59 | 3.8 | 8.9 | 12.3 | 6 |
| " | " | " | " | 17.6 | 58 | 4.0 | 11.9 | 10.5 | 4 |
| " | " | " | 680 | 14.1 | 65 | 4.0 | 12.0 | 15.0 | 6 |
| " | " | " | " | 14.0 | 64 | 4.9 | 12.0 | 15.4 | 4 |
| " | " | " | " | 14.2 | 67 | 5.5 | 12.0 | 15.0 | 3 |
| " | " | " | " | 14.2 | 68 | 7.1 | 12.0 | 15.5 | 4 |
| " | " | " | 650 | 11.6 | 58 | 0.1 | 27.6 | 6.9 | 17 |
| " | " | " | " | 11.6 | 58 | 0.5 | 44.6 | 5.4 | 10 |
| " | " | " | " | 11.6 | 58 | 0.8 | 23.3 | 6.9 | 19 |
| " | " | " | " | 11.6 | 58 | 1.7 | 26.0 | 9.0 | 9 |
| " | " | " | " | 11.6 | 58 | 2.6 | 37.7 | 5.3 | 6 |
| " | " | " | " | 11.6 | 57 | 4.9 | 12.3 | 10.0 | 4 |
| " | " | " | " | 11.6 | 58 | 5.7 | 11.2 | 15.3 | 4 |

TABLE I—*Continued*

EFFECT OF WIND ACTION ON TRANSMISSION LINES—TYPICAL CASES

Note: Columns 11 to 19 are included for cases *a* to *e* at the foot of the Table

| | 1<br>Cond. | 2<br>Diam. in. | 3<br>Weight per ft. (lb.) | 4<br>Span (ft.) | 5<br>Sag (ft.) | 6<br>Temp. (Fahr.) | 7<br>Wind (M. P. H.) | 8<br>Loop (ft.) | 9<br>Frequency (Cy. P. S.) | 10<br>Amp. 1/32 inch |
|---|---|---|---|---|---|---|---|---|---|---|
| | " | 0.904 | 0.783 | 725 | 17.7 | 35 | 4.2 | 18.0 | 19.7 | 24 |
| | " | " | " | " | 14.3 | 0 | 5.4 | 15.0 | 15.8 | 20 |
| | " | " | " | " | 13.9 | −11 | 5.7 | 15.0 | 15.8 | 20 |
| | " | " | " | " | 14.5 | 5 | 5.8 | 15.0 | 15.8 | 20 |
| (*d*) | " | " | " | " | 15.8 | 16 | 9.1 | 9.5 | 25.0 | 24 |
| | " | " | " | " | 16.9 | 38 | 10.2 | 14.0 | 19.7 | 24 |
| | " | 0.806 | 0.622 | 1000 | 23.4 | 46 | 4.8 | 16.4 | — | 2 |
| | " | " | " | 975 | 22.2 | 46 | 3.4 | 15.0 | 12.0 | 4 |
| | " | " | " | " | 22.2 | 46 | 5.7 | 14.5 | 11.8 | 17 |
| | " | 0.741 | 0.527 | 750 | 16.9 | 62 | 3.8 | 18.2 | 9.5 | 12 |
| | " | " | " | " | 16.7 | 59 | 4.9 | 12.3 | 18.5 | 9 |
| | " | " | " | " | 17.1 | 69 | 5.7 | 11.6 | 13.4 | 14 |
| | " | " | " | " | 16.8 | 60 | 6.8 | 12.3 | 16.3 | 7 |
| | " | " | " | " | 17.0 | 67 | 7.4 | 11.5 | — | 6 |
| | ACSR | 0.633 | 0.343 | 1020 | 19.8 | 54 | 4.9 | 4.0 | 30.0 | 4 |
| | " | " | " | " | 24.5 | 58 | 6.8 | 9.5 | 22.3 | 4 |
| | " | " | " | " | 26.2 | 70 | 8.5 | 12.0 | 17.2 | 6 |
| | " | " | " | " | 26.2 | 70 | 8.5 | 14.0 | 12.0 | 10 |
| | " | " | " | " | 26.2 | 70 | 14.8 | 4.0 | 45.0 | 2 |
| | " | " | " | 920 | 15.3 | 18 | 1.1 | 20.0 | 13.6 | 6 |
| | " | " | " | " | 17.0 | 37 | 5.5 | 10.0 | 22.0 | 6 |
| | " | " | " | " | 19.7 | 59 | 6.8 | 8.5 | 28.0 | 3 |
| | " | " | " | " | 16.0 | 28 | 9.1 | 8.8 | 26.0 | 4 |
| | " | " | " | " | 19.6 | 48 | 11.4 | 6.0 | 35.0 | 5 |
| | " | " | " | " | 18.1 | 42 | 14.8 | 4.2 | 52.0 | 1 |
| | A. C | 0.724 | 0.373 | 880 | 15.7 | 50 | 5.2 | 11.1 | 20.3 | 16 |
| | " | " | " | " | 15.7 | 50 | 5.7 | 11.9 | 20.0 | 21 |
| | " | " | " | " | 15.7 | 50 | 4.8 | 12.4 | 21.0 | 18 |
| | " | " | " | 860 | 14.9 | 57 | 1.1 | 18.8 | 18.8 | 10 |
| | " | " | " | " | 14.7 | 56 | 2.3 | 22.8 | 15.0 | 14 |
| (*e*) | " | " | " | " | 14.7 | 57 | 4.6 | 11.2 | 14.5 | 26 |
| | " | " | " | " | 14.7 | 57 | 6.2 | 9.4 | 16.0 | 13 |
| | " | 0.586 | 0.251 | 752 | 11.6 | 54 | 3.8 | 9.0 | — | 4 |
| | " | " | " | " | 11.6 | 54 | 5.5 | 9.0 | — | 2 |
| | " | " | " | " | 11.6 | 54 | 8.5 | 5.9 | — | 4 |
| | " | " | " | 583 | 10.9 | 55 | 1.0 | 14.0 | 11.8 | 9 |
| | " | " | " | " | 11.2 | 57 | 2.6 | 10.6 | 12.0 | 3 |
| | S. C. | 0.528 | 0.653 | 750 | 14.4 | 58 | 4.9 | 6.9 | 25 | 6 |
| | " | " | " | " | 14.4 | 58 | 6.8 | 6.9 | 32 | 6 |
| | " | " | " | 699 | 12.3 | 54 | 4.3 | 5.9 | 15.5 | 4 |
| | " | " | " | " | 12.3 | 54 | 7.2 | 4.0 | — | 1 |
| | " | " | " | " | 12.3 | 56 | 8.5 | 6.0 | — | 2 |
| | " | " | " | " | 12.3 | 54 | 9.2 | 6.0 | — | 12 |
| | " | " | " | " | 12.3 | 54 | 9.8 | 3.0 | — | 1 |
| | S. S. | 0.500 | 0.520 | 680 | 6.9 | 58 | 3.4 | 13.0 | 19 | 6 |
| | " | " | " | " | 6.9 | 58 | 3.6 | 10.3 | 20 | 4 |

| | 11<br>Tan. $Q$ | 12<br>$P$ | 13<br>$R$ (ft.) | 14<br>$Y'' - Y'$ (in.) | 15<br>$K$ (in. − lb.) | 16<br>$I_a M_a + I_s M_s$ | 17<br>$R K$ | 18<br>$I_d M_d$ Required | 19<br>$I_d$ Required ($M_d$ = 29,000,000) |
|---|---|---|---|---|---|---|---|---|---|
| (*a*) | 0.00709 | 9270 | 674 | 0.1390 | 1290 | 811,733 | 10,433,520 | 9,621,787 | 0.331,786 |
| (*b*) | 0.00687 | 4150 | 663 | 0.1280 | 531 | 478,763 | 4,225,836 | 3,747,073 | 0.129,209 |
| (*c*) | 0.00677 | 8500 | 682 | 0.1283 | 1091 | 337,173 | 8,929,236 | 8,592,063 | 0.296,278 |
| (*d*) | 0.01033 | 3260 | 292 | 0.1381 | 451 | 233,947 | 1,580,304 | 1,346,397 | 0.046,427 |
| (*e*) | 0.00604 | 2350 | 590 | 0.1863 | 438 | 87,127 | 3,102,240 | 3,015,113 | 0.103,969 |

Note: ACSR = Aluminum Cable Steel Reinforced.
A. C. = All Aluminum Cable.
S. C. = Stranded Copper.
S. S. = Stranded Steel.

energy consumption of the vibrating conductor. The small power required is noteworthy in view of the fact that the conductor in this case was 1.093 in. diameter, weighed 1.024 lb. per ft., and in some cases was under a tension of 9000 lb.

In order to obtain definite conditions at the point of support, a heavy cast-iron block was bolted to the framework near one of the pulleys. This block held a split steel bushing bored out to fit the conductor accurately and tightly. The distance from the end of this bushing to the center of the other pulley was exactly 48 ft.

A high power microscope was bolted to this block so that no relative motion between them existed. The microscope was then focused on the top of the conductor next to the end of the bushing. By means of an eyepiece micrometer the maximum longitudinal motion of a point on the top strand of the conductor was observed to be approximately 0.000656 in. with a tension of 9000 lb. The path of the observed point diminished longitudinally as the microscope was rotated from the top toward the side of the conductor, becoming more and more oblique and approaching a right angle with the longitudinal axis of the conductor on the horizontal transverse diameter. This last condition was due to the transverse motion of vibration and indicates that the strand fibres on the side are not subjected to pulsating longitudinal stresses as are those on the top and bottom of the conductor. No effect of longitudinal vibratory impact could be discerned and the effects noted above are undoubtedly due to simple transverse bending in the vertical plane. The transverse motions of the conductor were carefully noted and plotted. The resulting curves are sine waves for all loops not adjacent to a support. The supports distort the wave, producing a bending action adjacent to it and a point of inflexion in the first half of the loop.

FIG. 3—CAST-IRON BLOCK ON TEST FRAME

In all of the cases recorded in Table I, no breakage of strands has occurred except adjacent to a support or at a joint which had been either poorly designed or applied. It is a logical conclusion that if means can be found to prevent any sharper bending of the conductor at a support or at a joint, than occurs at the middle point of a loop, breakage due to vibration will be prevented.

Considerable thought and ingenuity have been expended upon the design of suspension clamps, but so far as the writer is aware no logical method has previously been developed to determine the proper shape of the conductor seat. The support cannot be regarded as a simple node and it is difficult to provide effective means for permitting the wave to pass through the suspension clamp without bending the conductor. The reason for this is that it is impossible always to have a wave impulse leaving on one side of a support at the instant it is arriving on the other. This is evidenced by recorded cases of broken strands while the conductor rested on a sheave.

TABLE II.

| | |
|---|---|
| Conductor | 795,000 cm. ACSR (54 Alum./7 St.) |
| Wt. per ft. | 1.024 lb. |
| Diameter | 1.093 in. |
| Span | 48 ft. |

| Tension lb. | Loop length ft. | Amplitude in 1/32 in. | Frequency cycles per sec. | Watts connected to conductor | Watts disconnected from conductor |
|---|---|---|---|---|---|
| 5500 | 48 | 112. | 4.27 | 8.10 | 6.75 |
| 5500 | 24 | 56. | 8.43 | 18.35 | 15.75 |
| 5500 | 16 | 30. | 12.67 | 27.01 | 27.15 |
| 5500 | 12 | 20. | 16.87 | 37.44 | 40.50 |
| 7500 | 48 | 104. | 4.87 | 10.05 | 7.90 |
| 7500 | 24 | 32. | 9.67 | 21.00 | 18.80 |
| 7500 | 16 | 24. | 14.33 | 34.03 | 32.10 |
| 7500 | 12 | 20. | 19.13 | 46.87 | 48.30 |
| 9000 | 48 | 102. | 5.33 | 10.73 | 8.80 |
| 9000 | 24 | 18. | 10.60 | 21.70 | 21.30 |
| 9000 | 16 | 16. | 15.67 | 34.20 | 36.50 |
| 9000 | 12 | 12. | 20.87 | 52.20 | 54.40 |

If the suspension clamp could be designed with a radius as large as that at the loop center it would be effective but it is difficult to do this within available limits of design. The angle of the conductor with the horizontal in a span of the greatest practicable length and sag at present in use, or contemplated, is about 23 deg. The summer to winter variation would be on the order of 2 deg. or 3 deg. while the vibration angle is less than ½ deg. The correcting means must therefore be applied to the moving conductor.

A simple and practical method is to apply to the conductor a layer of cylindrical rods at the support. Preferably each rod tapers at each end, thereby enabling it to be twisted around the conductor and held at the ends. This gives maximum resistance to bending at the support and a tapering mass on each side to prevent sudden reflection of waves at its ends. This arrangement is illustrated in Fig. 4.

The above conclusions are based upon the observations and experiments described and also upon the following theory. Referring to Figs. 5 and 6, the letters have the following meanings:

$L$ = Loop length = half wavelength
$A$ = Amplitude of complete vibration
$R$ = Radius of curvature at middle point of loop
$Q$ = Angle with axis at node point of freely vibrating loop
$F$ = Frequency of vibration in cycles per sec.
$V$ = Velocity of transverse wave in ft. per sec.
$P$ = Total tension in conductor in lb. (conductor not vibrating)
$l$ = Arc-length of loop

$W$ = Weight per ft. of conductor in lb.
$G$ = Acceleration due to gravity = 32.2 ft. per sec.
$K$ = Moment producing bending at support
$I$ = Moment of inertia of complete cable and damper at support
$I_s$ = Moment of inertia of steel-core of conductor
$I_a$ = Moment of inertia of aluminum part of conductor
$I_d$ = Moment of inertia of damper at support
$M$ = Virtual modulus of elasticity of complete conductor and damper
$M_s$ = Modulus of elasticity of steel
$M_a$ = Modulus of elasticity of aluminum
$M_d$ = Modulus of elasticity of damper material

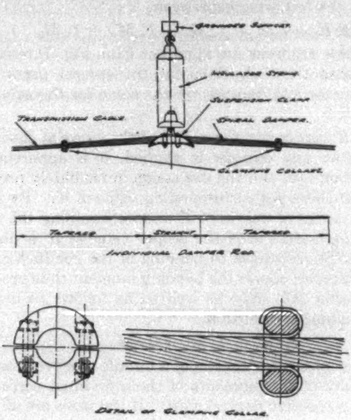

FIG. 4

$$V = \sqrt{\frac{P_e}{W}} = 2\,L\,F \qquad (1)$$

$$y = \frac{A}{2}\sin\theta = \frac{A}{2}\sin\frac{\pi\,x}{L} \qquad (2)$$

$$\tan Q = \frac{dy}{dx} = \frac{\pi\,A}{2\,L}\cos\frac{\pi\,x}{L} \qquad (3)$$

$$= \frac{\pi\,A}{2\,L} \text{ at origin when } x = 0$$

$$d\,l = \left[1 + \left(\frac{dy}{dx}\right)^2\right]^{1/2} dx \qquad (4)$$

$$\left(\frac{dy}{dx}\right)^2 = \frac{\pi^2\,a^2}{L^2}\cos^2\frac{\pi\,x}{L}$$

$$= \frac{\pi\ a^2}{l^2}\left(1 - \sin^2\frac{\pi\,x}{L}\right) \text{ when } a = \frac{A}{2}$$

$$d\,l = \sqrt{\frac{L^2 + \pi^2\,a^2}{L^2} - \frac{\pi^2\,a^2}{L^2}\sin^2\frac{\pi\,x}{L}}\,dx$$

$$\frac{\pi\,x}{L} = \theta,\quad x = \frac{L\,\theta}{\pi},\quad dx = \frac{L}{\pi}\,d\,\theta$$

$$d\,l = \frac{L}{\pi}\sqrt{\frac{L^2 + \pi^2\,a^2}{L^2} - \frac{\pi^2\,a^2}{L^2}\sin^2\theta\,d\,\theta}$$

$$= \frac{\sqrt{L^2 + \pi^2\,a^2}}{\pi}\sqrt{1 - \frac{\pi^2\,a^2}{L^2 + \pi^2\,a^2}\sin^2\theta\,d\,\theta}$$

$$l = \frac{2\sqrt{L^2 + \pi^2\,a^2}}{\pi}\int_0^{\frac{\pi}{2}}\sqrt{1 - \frac{\pi^2\,a^2}{L^2 + \pi^2\,a^2}\sin^2\theta\,d\,\theta}$$

This expression can be integrated approximately as follows:—

$$l = L\sqrt{1 + \frac{\pi^2\,a^2}{L^2}}\left[1 - \frac{1}{4}\,\frac{\pi^2\,a^2}{L^2\left(1 + \frac{\pi^2\,a^2}{L^2}\right)}\right.$$

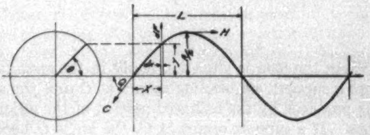

FIG. 5

$$\left. - \frac{3}{64}\,\frac{\pi^4\,a^4}{L^4\left(1 + \frac{\pi^2\,a^2}{L^2}\right)^2} - \frac{5}{256}\,\frac{\pi^6\,a^6}{L^6\left(1 + \frac{\pi^2\,a^2}{L^2}\right)^3}\right]$$

put

$$m = \frac{\pi^2\,a^2}{L^2} \text{ and } \sqrt{1 + m} = 1 + \frac{1}{2}\,m - \frac{1}{8}\,m^2 + \frac{1}{64}\,m^3;$$

consolidating:

$$l = L\left(1 + \frac{1}{4}\,m - \frac{3}{64}\,m^2 + \frac{5}{256}\,m^3\right)$$

$$l = L\left(1 + \frac{1}{4}\tan^2 Q - \frac{3}{64}\tan^4 Q + \frac{5}{256}\tan^6 Q\right) \qquad (5)$$

Since for any case of vibration recorded $Q$ is very small (not over approximately ½ deg.) tan $Q$ is small and $l$ is so little greater than $L$ that the tension $P$ may be taken constant. This is the fundamental assumption upon which equation (1) is based.

$$R = \frac{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{3/2}}{\frac{d^2 y}{d x^2}}$$

$$= \frac{\left[1 + \left(\frac{\pi A}{2 L} \cos \frac{\pi x}{L}\right)^2\right]^{3/2}}{\frac{\pi^2 A}{2 L^2}\left(- \sin \frac{\pi x}{2}\right)} \qquad (6)$$

$$= \frac{2 L^2}{\pi^2 A} = \left(\frac{1}{\tan Q}\right)\left(\frac{L}{\pi}\right) \text{ when } x = \frac{L}{2} \qquad (7)$$

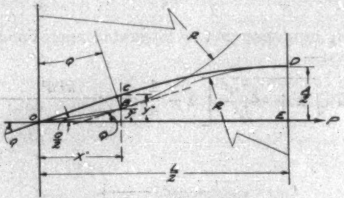

FIG. 6

When the loop is vibrating freely in the span, away from a support, no bending occurs at *O* and the angle *Q* is produced by the balanced motion of the adjoining loops. If a support occurs at *O*, the angle *Q* becomes zero at the left of *O* and the conductor is alternately bent up and down through the angle *Q*. Although the angle *Q* is small, the bending produces very considerable fiber stresses which added to the direct tension in the cable has produced breakage.

In Fig. 6, a circle of radius *R* is drawn tangent to the axis of *X* at the origin *O*. At a point *B* a tangent is drawn to this circle parallel to *O C*. This tangent makes an angle *Q* with the axis of *X*. The arc *O B* subtends an angle at the center equal to *Q* and the angle

$B\,O\,E$ equals $\frac{Q}{2}$.

The arc length *O B* is obtained as follows:

$$\text{Arc } O\,B = \frac{Q}{360}\, 2\,\pi\,R$$

Chord *O B* = arc *O B*, very nearly, since *Q* is small.

$$y' = O\,B \sin \frac{Q}{2} \qquad (8)$$

Since *Q* is small *X* may be taken equal to *O B* and substituting this value of *X* in equation (**2**):

$$y'' = \frac{a}{2} \sin \frac{\pi X'}{L} \qquad (9)$$

When the loop is freely vibrating the tension in the wire produces no bending at *O*. When bending occurs at *O* the resultant of the tension in the cable does not pass through *O* and the bending moment is the product of the tension and the offset of the bend.

Under the conditions indicated in the figure the bending moment at *O* is represented as follows:

$$K = P\,.\,B\,C = P\,(Y'' - Y'), \text{ very nearly.} \qquad (10)$$

In order to satisfy these conditions the following relation must obtain:

$$I\,M = R\,K \qquad (11)$$

In order to satisfy this condition, *I* must usually be greater than the value corresponding to the wire itself. This value may be obtained by a reinforcing wrapping or damper, the proportions of which may be determined from the following expression.

$$R\,K = I\,M = I_s\,M_s + I_a\,M_a + I_d\,M_d \qquad (12)$$

These relations are apparent from Fig. 7, remembering that the deflections for the several parts of the conductor and damper are the same for the same lever arm *h*.

If *R'* represents the radius of the curve at the right of 0 before any damper is applied, it is apparent from equation (**10**) and the discussion immediately preceding it that there is a corresponding value of *K*. By assuming a series of values of *R* and determining the corresponding values of *K* the proper value of *R'* is obtained when the resistance to bending of the conductor, without damper, equals the bending moment thus produced. Equation (**12**) may be written as follows to illustrate this balanced condition:

$$R'\,K' = I_s\,M_s + I_a\,M_a \qquad (13)$$

The moment of inertia of a bundle of wires is equal to the sum of the moments of the individual wires about their respective neutral axes. If the wires are all under tension and parallel the moment of inertia of the bundle may be taken as the sum of the moments of the individual wires about the neutral axis of the bundle.

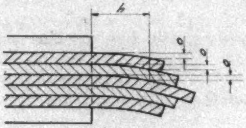

FIG. 7

In a conductor the wires are usually arranged in a spiral, which tends to equalize the stresses due to bending. On the other hand friction between the wires tends to counteract this effect.

Referring to Fig. 8 and first assuming the case at the middle of a loop, the individual strands are only restrained from slipping lengthwise with respect to one another by the friction between them produced by the conductor tension. Examining the behavior of an individual strand in the outside layer and denoting tension stress by the sign (+) and compression stresses by the sign (−), the part of the strand outside of the neutral axis of the complete conductor is (+) and the part inside is (−). At the crossing of the neutral axis the stress due to bending is zero. The small arrows indicate the direction in which the material of the strand tends to flow under the action of these stresses.

The adjacent strands of the same layer are moving almost synchronously with respect to each other. This is not the case, however, between the strands of adjacent layers and particularly where they cross each other at the neutral axis. In Fig. 8 the arrows indicate that while the outer strand tends to move toward the left the inner strand is trying to move toward the right.

If the strands of the successive layers were spiralled in the same direction much of this tendency would be removed. Steel cables designed to travel over sheaves are usually made this way and in a few cases of long river crossings the steel cores of A. C. S. R. have been so specified. However, the reversed lay construction is almost universally used for transmission conductors and so far as the writer is aware no conductor failure has been identified with this cause.

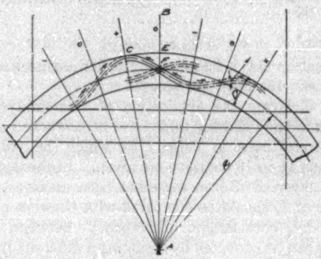

FIG. 8

If the strands are not restrained by friction, the fiber stress in each strand is due only to bending about its own neutral axis. Thus:

$$J_{Md} = \text{Max. Fiber Stress} = M_a \frac{d}{2R} \qquad (\mathbf{14})$$

If the friction between the strands were increased by any means so that all relative slipping ceased, then the maximum fiber stress would be expressed as follows:

$$J_{MD} = \text{Max. Fiber Stress} = M_a \frac{D}{2R} \qquad (\mathbf{15})$$

The true value of the fiber stress is somewhere between these extremes and is close to that given by equation (**14**).

Suppose now that a supporting clamp is applied to the conductor in such manner that all of the strands to the right of the line *A B*, Fig. 8, are prevented from slipping. The flow in the strand shown in Fig. 8 will no longer be equalized at *C* and a longitudinal stress approaching the value given by equation (**15**) will result. The strand which crosses line *A B* at *E* will not thus be affected and its stress will be represented by equation (**14**). Other strands have intermediate values of stress.

Referring to equation (**13**) the values of $I_s$ and $I_a$ will depend upon whether the neutral axis is taken at the center of the conductor or at the center of each strand. Similarly, the value of $R'$ will depend upon this same condition. The rather interesting fact develops that the fiber stress in the undamped conductor at the support is practically the same no matter which of these assumptions is made.

Table III represents one of the sets of observations given in Table I. The column headed $J_d'$ represents the fiber stress in the conductor at a support with neutral axis at center of each strand. $J_D'$ is the corresponding value with axis at center of conductor. Throughout this list these values are practically equal.

Table III further illustrates the effect of a damper cage consisting of seven aluminum rods each 0.475 inch diameter. In this case the radius of curvature is represented by $R_d''$, the fiber stress in the aluminum part of the conductor is given by $J_d''$ and the stress in the damper rods by $J_d'''$.

In this case the bending moments and stresses are based on the assumption that the neutral axis is at the center of the individual members of the entire conductor and damper.

In Table III the last two cases are hypothetical as regards loop length and amplitude for − 20° fahr. All the others are observed.

In the following nomenclature the subscripts *O*, 1, 2, 3, 4, 5, 6 refer respectively to the central wire and the successive layers of the conductor and damper from the center outward. The small letters $i_0$, $i_1$, etc., refer to the moments of inertia of the individual wires of the several layers. The large letters $I_0$, $I_1$, etc., refer to the moments of inertia of corresponding layers. The small letters $n_1$, $n_2$, etc., refer to the number of wires in each layer. The small letters $d_0$, $d_1$, $d_2$, etc., are the diameters of individual wires of the respective layers. The letters $M_0$, $M_1$, etc., refer to the respective moduli of elasticity of the materials forming the respective layers. $D_0$, $D_1$, $D_2$, etc., refer to the diameters of the circles circumscribing the respective layers.

Referring to Fig. 9:

$$d_0 = D_0$$

$$d_1 = D_0 \left( \frac{\sin \theta_1}{1 - \sin \theta_1} \right) \text{ when } \theta_1 = \frac{360}{2\, n_1}$$

TABLE III

Conductor—266800 c. m. A. C. S. R.
Stranding—6 x .2108" Alum.
7 x .0705" Steel

Diameter .633"
Wt. Per Ft. .343"
$E$ .2362
$H_a$ .885
$H_s$ .115

$(I_a M_a + I_s M_s)\, d = 5480$
$(I_a M_a + I_s M_s)\, D = 49160$
$(I_a M_a + I_s M_s + I_d M_d) d = 162900$—With 7 x .475" alum. damper

| Span (ft.) | Temp. (fah.) | $P$ (lbs.) | $L$ (ft.) | $A$ (1/32") | $F$ (C. P. S.) | Tan $Q$ | $R$ (ft.) | $J_{M_d}$ (lbs./$D''$) | $R_d'$ (ft.) | $J_d'$ (lbs./$D''$) | $RJ'$ (ft.) | $J_D'$ (lbs./$D'$) | $R_d''$ (ft.) | $J_d''$ (lbs./$D'$) | $J_d'''$ (lbs./$D'$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1020 | 54 | 2260 | 4.0 | 4. | 30.0 | .004090 | 311 | 254 | 46 | 1725 | 139 | 1710 | 288 | 274 | 619 |
| 1020 | 58 | 1825 | 9.5 | 4. | 22.3 | .001723 | 1754 | 45 | 122 | 650 | 361 | 658 | 658 | 120 | 271 |
| 1020 | 70 | 1710 | 12.0 | 6. | 17.2 | .002045 | 1867 | 42 | 103 | 768 | 315 | 754 | 572 | 138 | 312 |
| 1020 | 70 | 1710 | 14.0 | 10. | 12.2 | .002921 | 1525 | 52 | 70 | 1130 | 212 | 1120 | 413 | 192 | 441 |
| 1020 | 70 | 1710 | 4.0 | 2. | 45.0 | .002045 | 622 | 127 | 106 | 747 | 327 | 721 | 766 | 103 | 233 |
| 920 | 18 | 2370 | 20.0 | 6. | 13.6 | .001228 | 5183 | 15 | 146 | 542 | 442 | 548 | 800 | 99 | 223 |
| 920 | 28 | 2270 | 8.8 | 4. | 26.0 | .001859 | 1507 | 52 | 103 | 772 | 296 | 802 | 550 | 144 | 324 |
| 920 | 37 | 2135 | 10.0 | 6. | 22.0 | .002454 | 1296 | 61 | 78 | 1015 | 231 | 1028 | 433 | 182 | 412 |
| 920 | 42 | 2005 | 4.2 | 1. | 52.0 | .000974 | 1372 | 58 | 195 | 405 | 629 | 377 | 1283 | 62 | 139 |
| 920 | 48 | 1850 | 6.0 | 5. | 35.0 | .003410 | 560 | 141 | 58 | 1355 | 179 | 1325 | 334 | 237 | 535 |
| 920 | 59 | 1840 | 8.5 | 3. | 28.0 | .001444 | 1873 | 42 | 145 | 547 | 425 | 559 | 775 | 102 | 230 |
| 1020 | −20 | 2720 | 4.0 | 4. | 30.0 | .004090 | 311 | 254 | 41 | 1935 | 128 | 1850 | 250 | 316 | 714 |
| 1020 | −20 | 2720 | 14.0 | 10. | 12.2 | .002921 | 1525 | 52 | 56 | 1416 | 173 | 1370 | 313 | 253 | 570 |

$$d_2 = D_1 \left( \frac{\sin\, \theta_2}{1 - \operatorname{Sin}\, \theta_2} \right) \text{when } \theta_2 = \frac{360}{2\, n_2}$$

$$d_6 = D_5 \left( \frac{\sin\, \theta_6}{1 - \operatorname{Sin}\, \theta_6} \right) \text{when } \theta_6 = \frac{360}{2\, n_6}$$

$$I_0 = i_0 = \frac{\pi}{64}\, d_0^4$$

Assuming the neutral axes at the center of each strand:

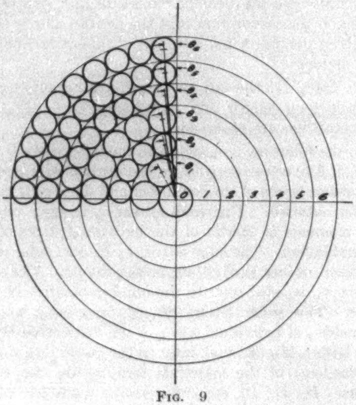

FIG. 9

$$I_1 = \frac{n_1\, \pi\, d_1^4}{64}$$

$$I_2 = \frac{n_2\, \pi\, d_2^4}{64}$$

$I_c$ = Total moment of inertia = $I_1 + I_2$ etc.

Assuming the neutral axis at the center of the cable:

$$I_1 = \frac{\pi}{64}\, n_1\, d_1^4 + \frac{\pi}{16}\, d_1^2\, (D_0 + d_1)^2$$

$$[R^4 \cos^2 \theta_1 + \cos^2 3\, \theta_1 + \ .\ .\ .\ + \cos^2 (2\, n_1 - 1)\, \theta_1]$$

Equation (**14**) is based upon the first assumption and equation (**15**) upon the second.

To illustrate the application of this analysis the values in the following table have been worked out for the several cases in Table I for which the values in columns 11 to 19 inclusive are given. In these cases a single layer of 12 iron wires has been assumed. The values of $I_d$ should be compared with those in column 19. Any considerable discrepancy between these values can be corrected by assuming a different number of wires for the damper. Also considerable variation is possible when different materials for the damper wires are used.

| Diam. of cylindrical part of damper wires. (In.) | Values of $I_d$ |
|---|---|
| 0.4153 | 0.578,253 |
| 0.3643 | 0.342,379 |
| 0.3333 | 0.239,959 |
| 0.3013 | 0.160,253 |
| 0.2413 | 0.065,928 |

Equation (**15**) was used in the above analysis.

The effect of the damper is not only to increase the radius of the bend at the support but also to reduce the amplitude, frequency, and loop length which still further reduces the fiber stress due to bending.

It may be added that dampers similar to the type described herein have been in operation in certain cases for about three years, without breakage of conductor strands, whereas before the application of the dampers, breakages had occurred within from two to three months after installation.

In conclusion, the fact remains that in none of the cases recorded herein does the total normal tension stress plus the bending stress in the aluminum part of the conductor reach the endurance limit values which have as yet been established by the usual laboratory methods. The inference is that the bending action at the support creates an unequal distribution of the stresses between the several strands alternately overloading some of them and relieving others. If this bending can be sufficiently restricted, the damaging results must disappear.

The problem has been approached in a different manner by Mr. G. H. Stockbridge, Engineer of Transmission, Southern California Edison Co. He has successfully suppressed vibrations by means of an ingenious device located in the span some distance from the support.

The writer is indebted for valuable assistance to Prof. William R. Work, and Mr. F. E. J. Litot, Carnegie Institute of Technology. Also to Messrs. L. W. Henry, M. E. Noyes, H. H. Rodee, L. H. Hemeter, L. D. Hutcheson, R. L. Templin, and G. W. Stickley, Aluminum Company of America.

## Discussion

**D. D. Clarke:** Mr. Varney's paper has been of very great interest to me, because he depicts a problem with which I have come in contact.

One item of vibration that he mentioned deserves more attention. When the span is divided into several of these vibration loops, the loops seem to travel from one end of the span to the other and back again. In these cases, such rough and crude measurements as we have made indicate that there was a change in the tension, longitudinally, of the wire. This would not amount to a great percentage of the stress in the conductor.

This is the first item of research that I have noted that covers a definite procedure with regard to quantities involved, and leads directly to solving the reason for certain things happening in conductors, that we know do happen. Here is a very definite field for providing the proper devices to eliminate breakage troubles, due to the fatigue of conductors, even the fatigue of supports of the conductors.

In our experience with several thousand miles of this sort of wire in service, the breakage of the conductors at the point of support has been nil, but the breakages of supports have indicated the necessity of getting into the problem, and I have a very optimistic outlook, because of this research as demonstrated in the paper.

**J. B. MacNeill:** Considerable work has been done, the last two or three years, in connection with the measuring of stresses in railroad tracks, by actual recording devices of a sensitive nature. I was wondering if anything similar had been done here, or if an adaptation of those devices would eliminate some of the assumption it has been necessary to make. Personally, while I do not know much in detail about these devices, I think there would be considerable hope of help in that direction.

**Eli Ettlinger:** There is one particular phenomenon mentioned by Mr. Clark, that I think is of significant interest, and that is the question of the appearance of travel of the wave along the conductor. To me, that indicates directly the fundamental phenomenon which is taking place in the vibration of the conductor, which perhaps has been something of a mystery and still, perhaps, is fundamental.

The setting up of a steady state of vibration can fundamentally be broken down mathematically, and physically can be so demonstrated, into two decaying traveling waves in opposite directions. The original train of traveling waves in one direction and the reflected waves from the distant end, when superimposed, develop these standing waves.

Perhaps with the wind acting on the various portions of the suspended wire, the fundamental traveling wave is not of the same length as the reflected wave, and therefore the standing wave has the appearance of moving along.

When we undertake to analyze this vibration problem, I think it is well to get to the fundamental physical conception of the problem, before we attempt to tackle the mathematical analysis of it. Mr. Varney's first paper, some years ago, gave something of the conception of those fundamentals, attempting to set forth the manner in which these vibrations are set up by the wind. So far, we know of no other particular reason for the appearance of these vibrations. If we analyze these vibrations in terms of the traveling wave related to the fundamental velocity which a traveling wave may have, due to the tension and mass of the wire, as shown in Mr. Varney's first paper, then perhaps from that we can begin to get an analysis of what is occurring on a rigid support. However, when we get to a semi-flexible support and then perhaps to the flexible support, we have no definite manner of analyzing the problem.

As I understand it, Mr. Varney has made his mathematical attempt here on the assumption that the support is rigid, which is not directly true on our ordinary suspensions on transmission conductors. I have in mind, directly in connection with the analysis on the rigid support, a very recent opportunity to observe the breakage of wires. It happens to be a case to which most transmission men have neglected to give their attention in the past, and that is to overhead ground wires.

I speak specifically of a ground wire of high-strength steel, rigidly attached to wood poles. I have three samples of the broken wire. The attachment was perfectly rigid, there was no chance of flexibility, and the indications of vibration were quite obvious. The breaks occurred directly under the rigid support. The breaks were characteristic in that case, as Mr. Varney said, as being clean-cut and not drawn as if tension were the cause of the trouble.

I think that perhaps the radius, as indicated for bends which may take place at the rigid support, is a very important item. We have development by Mr. Varney now, which gives us some idea of the importance of that item, and a means of determining its magnitude.

In the cases of breakage mentioned the repair was made by attaching a parallel piece of cable with Crosby clips, which at the same time furnished the additional mass along the wire accomplishing the same thing Mr. Varney indicates.

The fundamental thought, given in many texts, of the traveling waves as taking place on ordinary wires and the like, may well be kept in mind in attacking the vibration problem.

The tension and the particular materials that are used in conductors requiring certain tensions to give certain sags, develop certain span lengths, would seem to be of vital importance. I mention specifically that the particular ground wire which was in trouble was of high-strength steel. The thought occurred to me that, perhaps, if the ordinary Siemens-Martin steel had been used in its place, our difficulties might not have been as pronounced.

The relationship of tension to mass is a direct function of the velocity of propagation of the traveling wave on a wire supported by rigid supports or otherwise. It is my thought that where that velocity of propagation is greatest, where the tension is highest, perhaps the bending is sharpest at a rigid support. It indicates something with relationship to the steepness of the wave front of the traveling wave; that steepness of wave front brings to mind the kind of radius which will develop at the support. I am inclined to reduce tensions where possible on conductors, in order to hold down that particular factor, which I term the velocity of propagation.

The stringing tension of that ground wire, using high-strength steel under maximum loading conditions, would have been of the order of 5000 lb.; using a 3/8-in. Siemens-Martin would have given satisfactory clearance in the same case, and would have held our tension down to 3000 lb. The relationship of veloctiy of propagation would have been reduced by the square root of those tensions.

In closing I would suggest to Mr. Varney that, perhaps, the fundamentals with relationship to the traveling wave, which must first be set up in order to get these standing waves, is probably of as vital importance in the study of this problem as the pure phenomena of the standing wave.

**Theodore Varney:** Replying first to Mr. MacNeill's question, I understand him to ask whether we have tried to carry on any accurate laboratory experiments whereby we measure the movements and stresses set up in the individual strands of the cable.

We must admit that our experimental work has lacked refinement. At the Carnegie Institute of Technology in Pittsburgh where we have been experimenting for the last year with the wooden frame and cable, we have not yet been able to work out any very accurate method of recording these experiments. As far as I can see, it will be difficult to obtain such records. We have tried to detect with a high-power microscope the actual movement of the particles of the cable but we could do this only in the outside strands.

The idea we had was, I think, similar to what Mr. Ettlinger suggests, *viz.*, the rather high velocity of a vibration or standing wave in a cable at pretty high tension conveys the thought of impact. That is what we tried to check with the microscope, but when we found we could not observe any longitudinal motion in the strands at the side of the cable, we came to the approximate conclusion that the stress effect was confined to bending.

Mr. N. B. Obbard, of the American Bridge Company, at Pittsburgh, once suggested to me the theory that the resulting wave in the conductor might be due to the combined effect of torsional, longitudinal, and transverse vibration.

The transverse wave predominates, but there is of course a very slight longitudinal varying stress which must set up a wave some 10 or 12 times higher in velocity than the transverse wave. There must also be present a slight amount of torsional vibration due to the spiral effect of the strands.

The point Mr. Obbard made was that if the period of the natural torsional vibration coincides with the eddy frequency of the wind, the transverse vibration would be amplified on the same principle as that used by Floettner in the rotating masts of his ship.

Since the longitudinal vibration might also have the effect of setting up transverse vibration, if of a proper frequency, Mr. Obbard thought all three might combine in some proper phase relation to account in some measure for the large amplitudes recorded in certain cases.

The speaker has no data to substantiate this theory and is rather of the opinion that the large amplitudes are explained by resonant conditions of the conductor with its system of supports together with a steady wind velocity acting uniformly over a considerable length of line.

I should like to add that this paper is not an attempt to go into deep mathematics. Mathematics have been introduced simply in the effort to explain observed effects. The theory of the radius of bending affords a simple explanation of what goes on in a conductor when it vibrates and further affords a simple remedy.

It is true if you add stiffness you will reduce the amplitude. Just how much is difficult to say without actual experiment, but just in proportion as the amplitude is reduced the vibration will be "damped." In other words, the damper scheme reduces the stresses to a safe point even if the amplitude were not reduced, but in addition to this if it reduces the amplitude we are still further on the side of safety.

It is true that the theory developed in this paper is based on the assumption of a rigid support which is not actually the case in any transmission line. It is believed, however, that whatever flexibility is provided by a well designed pivoted suspension clamp or other means is in the direction of additional safety. All that the writer has said as far as he can see, applies just as well under such conditions with probably improved results.

As to the question of tension in the cable, it is true that if tension is reduced the bending moment is reduced, provided the amplitude remains the same. Very often, however, when a cable is strung slack, "whipping" results. Whipping, as the speaker understands the term, is merely a low-frequency vibration of large amplitude. Such a vibration has been known to have very destructive effects. The type of damper described in this paper will tend to limit whipping.

The point is, if it is not necessary to string the conductor tight, don't do it; but if there is an economy to be gained, do not hesitate to do so. In either event, suitable safeguards against vibration or whipping should receive consideration in the construction of any transmission line.

# The Planning of Telephone Exchange Plants

BY W. B. STEPHENSON[1]
Non-member

***Synopsis.**—This paper discusses procedures followed in planning future extensions to telephone exchange plants to care for increased demand for telephone service. An outline is given of the methods employed in forecasting future demand for telephone service and in determining the most efficient design of the plant to meet the service requirements. The uses made of engineering comparisons in solving the economic phases of various kinds of telephone engineering problems are discussed, with particular reference to location and size or extent of major items of plant as well as the time when they should be ready to give service. Emphasis is placed upon the importance of those factors less readily evaluated, such as service factors, practicability from a construction and operating standpoint, flexibility, etc.*

* * * * *

TELEPHONE engineering involves many widely varying problems. Among these is the design of the various component parts of the telephone plant. This includes the design of central office buildings, the design of switching and power equipment to be housed in these buildings, the design of the trunk cable system with any loading necessary in order to connect these buildings, and the design of the distribution system. The distribution system includes, of course, the conduit, pole lines, feeder cable, distributing cable, house cable, etc., necessary to reach the subscriber's premises and connect his station equipment with the switching equipment in the central office.

Before the building can be designed in detail, however, determinations must be made as to whether the building should be built at all, where the building should be located, when it should be ready for occupancy, what area will be served by the building, and how much equipment must ultimately be housed in the building. Before the equipment for any particular building can be designed, we must know what type of equipment should be used and about how much business will be handled on this equipment. Before the trunk plant can be properly designed, we must know our future plans for increasing or decreasing the operating centers in a city, how much business will be handled on this trunk plant, and the economic allocation between transmission loss in the trunk plant and the transmission loss in the distribution plant. Before the distribution plant can be designed, we must know our future plans for serving the area involved. In other words, it is evident that a large amount of broad preliminary planning must be done before the detailed design of a telephone exchange plant can be undertaken.

It is the purpose of this paper to give a general idea of the methods now in use in this preliminary planning. The discussion will be confined to the exchange plant problem for the larger towns and will not go into the toll plant problem. To avoid confusion a "telephone exchange plant" will be defined as that plant serving a single community, for example, the "St. Louis exchange," or the "Kansas City exchange." An "operating center" will be defined as that part of the exchange plant housed in one building. There are thus several operating centers in a large exchange.

The first step in attacking the telephone planning problem for a city, is to make a determination as to about how much business will be cared for. This problem is attacked on very broad and thorough lines. An attempt is made to arrive at the estimated population of the city in question for some 18 or 20 years hence and also for intermediate periods of about 6 and 12 years. From these estimated future populations and other careful studies, which will be touched upon briefly later, an estimate is made as to the number of telephone stations and lines which will be in service 6, 12, and 20 years in the future. Moreover, this survey shows the location of these lines and stations.

It has been found that the various parts of a city have wide differences in market conditions or, in other words, the possibilities of selling telephone service. One of the first steps in making a survey is to divide the town up into so-called market areas or areas which display somewhat the same economic characteristics. These market areas are further broken down for convenience sake into what is known as "house-count sections."

The accompanying map (Fig. 1) indicates for an assumed case how a city is divided into market areas and house count sections for purposes of a survey. Market area "A," for example, would consist of the downtown business section which includes all the office buildings, department stores, hotels, and large retail firms together with some warehouses and manufacturing plants along the two railroad lines. Market area "H," for example, might be a residence area with the medium classes predominating, while market area "D" would consist of the highest type of residence district, including very little neighborhood business.

After the above divisions in the area of a city have been made, a card record is made of all the existing subscribers. These cards show the name, the telephone number, and the address of each subscriber. These data are then summarized on field survey sheets which are made up by blocks. The field men then

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[1] Southwestern Bell Telephone Company, St. Louis, Mo.

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take these sheets and go out into the field, visit the block covered by each sheet and for the business subscribers indicate the class of business, and for the residence subscribers the type of residence, and the estimated rental classification, that is, the estimated amount of rent that the subscriber is paying. The rental classification is merely a convenient means of arriving at some kind of an idea of the economic status of the family. It has been found that the market for telephone service is better among those subscribers who are better able to pay for this service and that there is rather a direct relation between the rental classification and the market for service in any one market area. This will be different for the various market areas, however. For example, a $40 rental in a market area inhabited by university people will represent a better market for telephone service than a $40 rental in an area inhabited by steel workers.

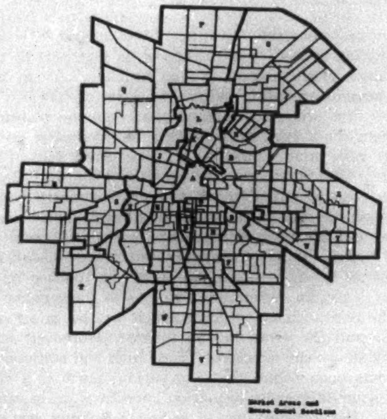


FIG. 1

These field sheets are later summarized so that we can tell about what percentage of the residence subscribers of the various classifications in the various market areas take telephone service and what class of service they take, that is, individual lines or party lines. These summaries also indicate the amount of neighborhood business and the amount of downtown business. The completion of the surveys then has given us very detailed information on the present market conditions for telephone service in the city in question.

In making an estimate for the future, the first and possibly one of the most difficult tasks is to arrive at an estimated population of the city for some 15 to 20 years hence. This problem is attacked on broad lines. Periodic estimates are made of the population of the United States, taking into account emigration, immigration, and the excess births over deaths. Similarly the estimated population of the United States is broken down by states and later distributed to the cities and other communities. This gives us the best possible estimate of the future population of the city in question. This estimate takes into account, not only local conditions, such as the trend of manufacturing, railroad facilities, etc., but also the national trend. These estimates of population are made in an impartial manner. Population estimates made by city boosters are inclined to be tinged with the hopes of the individual estimator, but every effort is taken to eliminate this factor from the estimates made for telephone purposes.

Data are at hand showing the average size of the families of the city in question and also the trend as to the increase or decrease in size of families. From the estimated future population, and estimated persons per family, the estimated number of families is obtained. Based upon the intimate knowledge of the city which was obtained in the survey, an estimate is made as to the number of families which will live in the various house-count sections in the city. Based upon the knowledge of the business in the town obtained from the survey and the relations which exist between business firms and residence population, an estimate of the future downtown and neighborhood business firms is obtained. From these residence and business data, an estimate of the future market for telephone service in the city is arrived at.

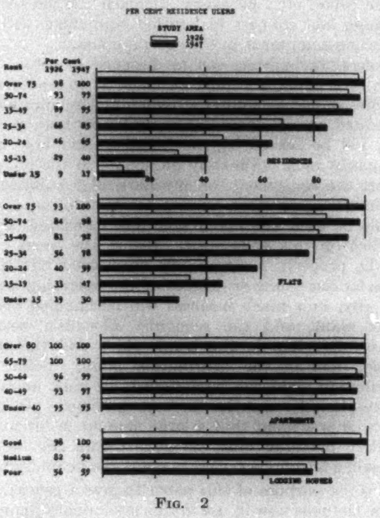


FIG. 2

It is thought that the accompanying Fig. 2 showing a typical per cent residence users will be interesting. It will be noted that the percentage of users in the various rental classifications is different for different kinds of dwellings, that is, residences, flats and apartments, and lodging houses.

A large map of the city is prepared and the estimated number of telephone lines for the future period is placed in each city block, which gives the best possible data for the planning of the telephone plant. The accompanying map (Fig. 3) is a spot map showing one spot for each ten telephone lines. The map has been prepared in spot map form since this will give a better idea of the telephone density than a map showing the number of lines in each block. The map showing numbers of lines is used in the actual calculations, of course, instead of the spot map.

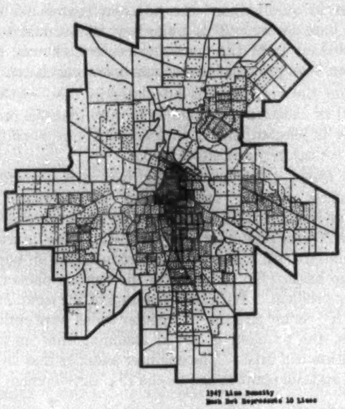


FIG. 3

The next problem is to determine the number of operating centers which will be required to serve the city and the best location for these operating centers. It would probably be physically possible to serve some of our larger cities from one operating center. This would involve an enormous equipment building at some central location and it would be necessary to provide cables connecting all the subscribers in the city to the one building. It is apparent that the average length of the subscribers' lines in this case would have to be very high. In order for the subscribers farthest from the operating center to be able to talk, it would be necessary to use wire of very large comparative diameters or take some other expensive means for eliminating undue transmission loss. In a city of perhaps 100,000 population, it might be necessary to consider seriously a single center plan, but it is obvious that in the case of the larger cities such an arrangement would be out of the question.

It would also be possible to go to the opposite extreme and place a little operating center in each block in the the city. In this case, the length of the subscribers' lines would be very short, being all less than one block long. All of these little centers, however, would have to be connected by trunks making a tremendously expensive trunk plant. Arrangements would have to be made to provide switching and transmission power at each one of these little centers and the cost of all of these little buildings would probably be much greater than the cost of fewer but larger buildings. This arrangement is obviously impossible from an economic standpoint and impracticable from a physical standpoint, and the correct answer is some place between the one center and many center plans.

The method followed in solving these problems, will be illustrated by assuming a sample problem and carrying through the line of reasoning. The sample problem is rather a simple problem for a small city, but exactly the same principles are involved as in the larger towns, such as St. Louis. This is the type of problem which is met today in most of our cities.

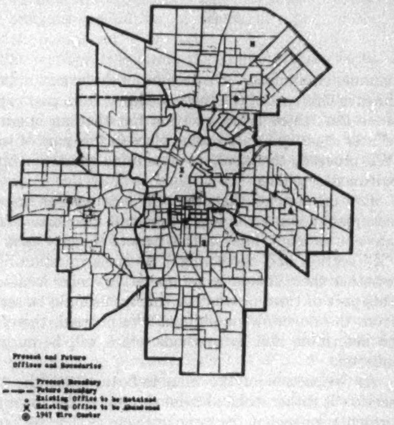


FIG. 4

The accompanying map (Fig. 4) indicates for our assumed problem the present centers, the present boundaries between the centers, and the future centers with the future boundaries which are determined by our studies.

Let us assume that the downtown "X" center has new dial type equipment housed in a new building. Very careful studies were made before this building was built, of course. A large investment is involved in this building and equipment which were designed so that they can be extended to last for many years. It is a safe assumption, therefore, that this building will be retained at its present location. Let us also assume that the "Y" operating center has just been built as a result of careful studies and is also designed to last for many years. On account of the large investment involved here, it is a safe assumption that this building will also be retained at its present location.

The "Z" building is several years old and houses manual equipment. On account of the large number of lines in this part of the town, we know from past experience that there is no question but that an operating center must be located some place in this part of town. We proceed, therefore, to determine what the future wire center will be.

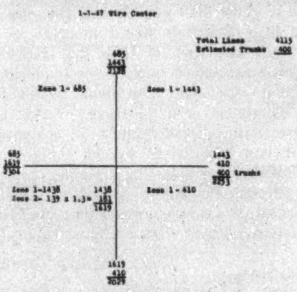


FIG. 5

Let us assume that the "M" center has manual equipment located in less permanent quarters. There are not so many lines in this part of the city as in the "Z" section and there might be some question as to whether there should be an operating center located in this part of town or whether this area should be served from the downtown building. We proceed, therefore, to determine this by methods which will be outlined later on.

An inspection of the map indicates that the "A" section is rather isolated from the rest of the town and presents somewhat the same problem as the "M" area, except that the "A" area is somewhat smaller and is now served from the downtown building. There is some question as to whether there should be a center in this part of town and we proceed with a solution of this problem together with a determination of the proper wire center.

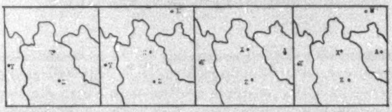
In the above paragraphs, the term "wire center" has been mentioned several times. A wire center may be defined as that location for an operating center at which the cost for subscribers' lines and trunks will be a minimum. The determination of a wire center is a cut-and try-problem which can be illustrated by the accompanying Fig. 5, illustrating the wire center for the "A" area.

From an inspection of the "A" area, a trial center is selected and axes are drawn on the map through this center following the direction of the principal streets. The lines in each quadrant are then equated in terms of the cost of the finest gage of conductor contemplated and summarized. The inter-office trunks are also included in this calculation. If it is found after these lines are counted that the sum of the equated lines in the various quadrants does not balance, a new center is tried to determine a better balance. When a balance is obtained, this point will be a wire center.

It is necessary to assume a boundary between the center in question and the adjacent centers for each trial wire center. This boundary is assumed to be equidistant from the operating centers, that is, each station is served from the nearest operating center.

After the wire center is calculated by these methods, practical checks are applied to be sure that the proper center is selected, taking into account local conditions as to topography and street layout.

In order to determine the best arrangement of operating centers, various trial arrangements are assumed, and certain costs involved in serving the city at the 20 year period (in this case 1947) in the future are calculated. All these costs are reduced to an annual charge basis. Fig. 6 indicates the various plans tried in our problem. With the exception of the locations of the "X" center and the "Y" center which were outlined above, the problem is solved assuming that an ideal condition will exist. The engineer assumes that he can build an ideal plant to handle the 1947 development and he has not taken into account any losses which might be occasioned due to the fact that the present plant would not fit in well with the ideal 1947 plant. The method of caring for the effect of the present plant will be outlined later on.



| PLAN I | PLAN II | PLAN III | PLAN IV |
|---|---|---|---|
| 3 Centers | 4 Centers | 4 Centers | 5 Centers |
| 7 Units | 7 Units | 7 Units | 7 Units |

FIG. 6—1947 COMPARISON

The above arrangements are compared as regards annual charges for each of the following items:

Subscribers' lines
Trunks
Central office equipment
Maintenance labor
Land

It is necessary that the trial arrangements of operating centers be chosen with great care, so that the comparison of the results of the various plans will give a direct comparison of the results of some possible program with some other possible program. In other words, each plan must differ from some other plan by one variable only.

By reference to Fig. 6, it will be found that plan No. 1 assumes an office at the present "X" location and at the present "Y" location. A center has also been assumed at the "Z" wire center which has been calculated as outlined above.

Plan No. 2 is exactly the same as plan No. 1 except that an "M" center has been added at the wire center of the "M" area. A comparison of plan No. 1 with plan No. 2 will therefore give a direct indication as to the economies of an "M" operating center.

Plan No. 3 is exactly the same as plan No. 1 except that a center has been added at the wire center of the "A" area. A comparison of plan No. 3 with plan No. 1 will, therefore, give a direct indication of the economies of having an operating center in the "A" area.

While plan No. 2 and plan No. 3 will give an indication as to the economies of an "M" or an "A" center, the downtown "X" center will be smaller, of course, if both the "M" and "A" centers are in existence than if only one of these centers were in existence. In order to check whether this would make any material difference in the economies of the arrangement of operating centers, a further plan No. 4 was prepared which assumes both an "M" and an "A" center.

Referring again to Fig. 6, it will be found that the first item of cost to be considered is that of subscribers lines or in other words, the cost of the conductors (including conduit) to connect the subscribers' telephone instruments with the operating center. The conductor requirements are determined for each plan, and suitable annual charges are applied. The annual cost of subscribers' lines is larger for any plan which has fewer centers since the only economy which can be obtained by opening an additional operating center, is a reduction in the cost of the subscribers' lines.

Whenever an additional center is added, it is necessary to connect this center by means of trunks to all the other centers in the city so that subscribers served from this new center can talk to any subscriber served by any other center. The trunk cost, therefore, will increase each time a center is added. An estimate is made of the flow of traffic between the various centers, from which estimate the number of trunks is derived. Knowing the grade trunk required to give proper transmission, the cost may be inferred.

Central office equipment is placed in the building at each operating center, of course, to furnish talking power to the subscribers and to furnish a means of switching connections between subscribers. The cost of the central office equipment increases somewhat when an additional center is added, due to the fact that it is necessary to provide a power plant and other common items of equipment for each building, and due to engineering and installation costs. In order to arrive at the equipment costs an estimate is made of the lines, terminals, originating calls, and calls trunked to and from other units of equipment, based on the estimated telephone development for the 20 year period. From these data, the requirements for various parts of the equipment are calculated and priced.

If a new operating center is opened, sufficient equipment would not be installed to last for the 20 year period covered in our growth estimates, of course, because the carrying charges on the idle equipment would be prohibitive. A considerably smaller amount of equipment would be installed, and additions would be made from time to time as required by the increasing number of subscribers.

An engineering and installation cost is involved each time an addition is made to this central office equipment. If more centers are added in a town, therefore, we will be adding equipment for growth to each of these centers, resulting in more but smaller additions. These engineering and installation costs do not decrease in proportion to the decrease in size of the addition; that is, these costs for a 2000 terminal addition will, in general, be more than one-half the cost for a 4000 terminal addition. Thus more centers will result in greater engineering and installation costs. These costs are capitalized, of course, as a part of the cost of the equipment.

In like manner, it is found that the operating costs, such as maintenance or other labor, and the costs of buildings and land are greater whenever an additional center is placed in a town. The maintenance labor is estimated by determining the number of men required and their salaries. Building costs are estimated by determining the required building volume.

Let us assume that the summation of the above annual charges for our problem indicates that Plan II and Plan III are each lower than Plan I (Fig. 6) and that Plan IV is also lower than either Plan II or Plan III. This indicates some economies for operating centers in the "M" and "A" areas as of 1947. As previously stated, the above calculations are based largely on being able to construct an ideal plant as of 1947 with no penalties due to the plant now in service. This is obviously an impossible condition and the above results, therefore, can be taken as only a broad general indication of the best method of serving the town. Obviously the above results give no indication as to when an operating center should be opened. It will be necessary to study each major move individually with the above results in mind.

Since there is already a center in the "M" area and the subscribers' cable is centered to this location, and since the indications are favorable to a center in this area for the 1947 period, there is little question but that the center should be continued. The present equipment is manual and the next big problem in this area will be to determine what to do when the manual unit is filled and cannot be extended without some major move.

In the "A" area (at present served from the downtown building), our assumption as to annual charges indicates that at some time it will probably be advisable to open an operating center. We have no indication, however, concerning at what time this center should be opened. We know from past experience that in general the best time to open a new center in an area is that time at which it would be necessary to make some major move if the center were not opened. For example, since the "A" area is fed from the downtown building, a time might arise when it would be necessary to make some major move downtown to handle the growth, such as a large building extension, with the possibility of postponing this move if a center were opened in the "A" area. On the other hand, the cable or conduit which feeds the "A" area might become filled so that a very large expenditure would be involved to reinforce these facilities if we continue to feed this area from the downtown building.

Let us assume that the latter condition exists in the "A" area. The feeder cables serving the section are located in conduit, the last duct of which will soon be used. It would be necessary to reinforce this conduit in the latter part of 1928 and place additional cable if the section were fed from the downtown building. This reinforcement will be expensive due to the fact that a portion of the reinforcement will involve rock digging. Knowing from the above studies that a center in the "A" section will probably be economical at some future time, the question immediately arises as to whether it would not be better to open this center in 1928 rather than to make the expensive conduit reinforcement and add more cable.

In order to solve this problem, reference is made to the estimated telephone development of the "A" area and the downtown area for the 20 year period and the intermediate periods, as developed from the commercial survey data. Based upon this estimated development, an estimate is made of all the building and equipment additions which would have to be made downtown between 1928 and 1947 both with and without an "A" center. An estimate is also made of the expenditures for conduit and cable which would be required, between 1928 and 1947, both with and without an "A" center. An estimate is made of the amount of equipment and the size of the building which it would be necessary to provide if the center were opened in 1928 and an estimate is also made of the additions which would have to be made to this building and equipment between 1928 and 1947. These various amounts of plant are priced and the annual charges are inferred. Since the investments and annual charges would vary between plans throughout the period between 1928 and 1946, the annual charges are placed on a present worth[2] basis. The following table indicates the results of this present worth study.

PRESENT WORTH 1929-1947

| | Plan I<br>Operate from "X" | Plan II<br>Open New Office |
|---|---|---|
| Aerial cable | $ 55,966 | $ 45,812 |
| Underground cable | 187,243 | 41,706 |
| Underground conduit | 59,868 | —— |
| Salvage on displaced plant | −26,559 | −42,521 |
| Building including house service | 28,922 | 108,678 |
| Land | —— | 4,306 |
| Central office equipment | 334,998 | 477,597 |
| Excess maintenance | —— | 69,883 |
| Number changes | 2,184 | 14,500 |
| Traffic saving | —— | −8,496 |
| Excess inter-office trunks | —— | 10,764 |
| Total | 642,622 | 722,229 |
| Excess | | 79,607 |

NOTE: The above does not indicate the total cost of serving the area, of course. The cost of much of the plant which will be required under either plan, has been omitted as being common to both plans.

This investigation, as summarized on the chart, tells us that, in so far as the various factors can be evaluated, the center should not be opened in 1928 but that the conduit should be reinforced and cable added instead. These data do not tell us when the center should be opened. It will be necessary to watch this situation in the future. and consider the problem again from time to time in much the same manner as above.

Since the data are available, the annual charges both with and without the "A" center are obtained for 1928 and for 1946. These annual charges are then plotted upon a graph as given in Fig. 7 and the annual charge points are connected by a straight line. It is appreciated, of course, that this annual charge will not be a straight line between 1928 and 1946 but will be irregular due to the periodical additions of plant and the straight line, therefore, is only a general indication. Our studies have told us, however, that if the "A" area grows as estimated, and if there are no unforeseen changes in the art, we will probably find it advisable to open an operating center in this area at some future date.

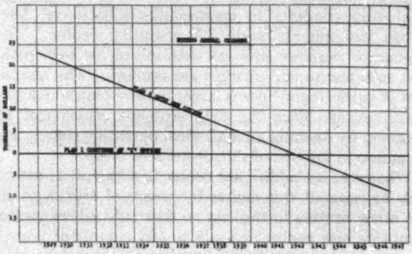


FIG. 7

The above discussion on the determination of the proper number of operating centers for a town and the determination of the wire centers for these operating

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2. The present worth of a given sum of money due at the end of a given time is the sum that, put at compound interest for the given time, will amount to the given sum when due.

centers has indicated that the location for a telephone building is determined by the number and location of the subscribers to be served by that building. The number and location of the telephone subscribers is in turn the result of many factors, such as the topography of the town, real estate development, transportation, etc. It is apparent, therefore, that it will at times be necessary to build a telephone building in a residence area. When this is necessary, however, special care is taken to build a suitable and attractive building. The general architectural appearance is made to harmonize with the neighborhood. The set back in general use in the neighborhood is observed. Generous yards are provided, and these yards are made attractive by suitable treatment with shrubbery. In other words, every effort is made to make the building a welcome addition to the neighborhood.

The studies illustrated above have enabled us to reach the following conclusions:

1. The wire center in the "Z" area for the 1947 development is indicated by our calculations to be a considerable distance south of the present building. When it becomes necessary to erect a new building in this area, the trend of the future development, therefore, indicates that we should consider a location for the new building considerably south of the present building. The present building, of course, has been in service many years and was located as nearly as possible on the economical center for the development to be served by this building during its life. The new building, however, will serve a somewhat different area, and the trend of future development is towards the south.

2. We can conclude that there should be an operating center in the "M" area. The conditions in this case are somewhat similar to those in the "Z" area and will call for similar treatment in the light of conditions in the area.

3. We have determined that, from an economic standpoint, the conduit which feeds the "A" area should be reinforced in 1928 and additional cable placed between the area and the downtown building, thus deferring the opening of a new center in the "A" area for the time being.

4. We have obtained indications that it will probably be economical at some future date, to open an "A" center. It will be necessary to keep this in mind and make a further study of this question whenever it is necessary to make some major move which could be postponed if the center were opened.

Mention has been made above of the introduction of dial equipment in some of the offices. The question of when and how dial equipment should be introduced into an exchange is one which must be very carefully considered. As a general rule the most favorable time for the introduction of dial equipment is when it would be necessary to make some major move to care for the further growth in the area served by the operating center.

In developing the program to be followed in offices which are still on a manual basis consideration must, of course, be given when the necessity for a major move arises, to the question as to whether the use of this type of equipment should be extended for a further period or whether the dial type should be introduced.

It would, of course, be unwise from a physical and financial standpoint in one of the larger cities, St. Louis, for example, to undertake to change all of the manual equipment to dial equipment at one time. Since the manual equipment is entirely satisfacory for present conditions and much of it will be continued in service for some time it becomes necessary to devise interconnecting equipment whereby new operating centers as they are introduced may be of the dial type and be connected with and operated with the existing manual equipment. All of this has been satisfactorily accomplished and the costs of such equipment are reflected in the various cost studies.

There are two types of dial equipment, the so-called "panel" type equipment and the so-called "step-by-step" type equipment. Panel equipment has been designed primarily to meet the conditions in the larger exchanges, such as St. Louis, while step-by-step equipment is usually employed in the medium sized and smaller exchanges.

Referring to the above problem in the "M" and "Z" areas, careful studies made some time ago have indicated that the growth can be handled economically without any major moves by adding manual equipment. A major move will be required at "Z" when the manual unit is filled, when it will either be necessary to start a new manual unit or to start a new dial unit. Our studies outlined above indicate that if a new center is opened in the "Z" area, the building should be located about a mile south of the present building.

The problem in the "Z" area can be stated specifically as follows:

a. The "Z" area is served from one building which is considerably off the wire center for future development, for reasons previously outlined. The building houses one manual unit which will soon be filled, making it necessary to provide some major relief.

b. The preliminary indications are that the "Z" area should be served from one building in the vicinity of the wire center, overlooking for the moment the factors involved in making such a move.

Questions:

a. Should this new unit be located in an addition to the present building to conserve existing plant, or should a new building be erected nearer the wire center for the purpose of decreasing future investments in plant to care for future growth?

b. Should the new unit be of the manual or dial type?

c. In case the new unit is to be of the dial type, should enough equipment be installed for growth only, or should enough be installed to displace the manual unit?

In order to answer the above questions, it will be necessary to consider in detail each of several possible construction programs. Having determined the factors involved in the various possible programs, the engineer proceeds with the analysis of each of these programs. Possibly one or more programs can be eliminated due to practical considerations, and careful cost studies may eliminate other programs from an economic standpoint. In case cost studies are necessary, they will probably be of the present worth type, which was outlined above, for use in the question of opening a new center in the "A" area. In fact, this problem is somewhat similar to the problem outlined above for the "A" area, except that this problem is considerably more complicated, due to the presence of a building in the area. Taking all factors into account, one program is finally determined to be the most favorable to meet the needs of the particular situation.

Another type of problem has to do with the question of economic allocation of the transmission loss between the subscribers' plant and the trunk plant. This is determined by what are known as "loop and trunk studies." The data developed in connection with the commercial survey mentioned at the beginning of this paper together with comparable estimates of inter-office truck requirements, are largely used in the solution of this problem.

This problem is generally solved for an estimated development of a considerably less remote period than the 20 year figure used in some of our work. This is because the results of these studies are used for immediate engineering of extensions to the cable plant. The life of this plant in general is less than the life of central office buildings, and moreover it is relatively easy to make some adjustments in grade of conductors by making cable throws.

The estimated development indicates the numbers of lines which will be in service in each central office area at the future date selected and the lengths of these lines. Knowing the number of lines, the number and holding time of the calls flowing between offices are estimated and from this, the numbers of inter-office trunks on the various trunk routes are calculated.

In order that subscribers can talk satisfactorily in any exchange, the plant must be designed to conform with generally recognized transmission standards, these standards being set after individual consideration of all the factors peculiar to any one area. These standards represent a grade of transmission which experience has indicated will be thoroughly satisfactory to the subscriber and at the same time permit the development of an economical plant.

In a multi-center exchange area, the transmission loss is distributed principally between the subscribers' loops and the trunks, that of the station and central office equipment being relatively constant. In order to attain the desired standards, consideration must therefore be given to designs which will economically apportion the loss between the two classes of plant. It would be possible to provide the cheapest subscribers' plant available and make up the required transmission in an expensive trunking plant or vice versa. Obviously, either procedure would not permit of obtaining the desired transmission with an economically balanced plant.

Knowing the numbers and lengths of the lines and also the numbers and lengths of the various inter-office trunks required, as outlined above, the costs of the trunk and subscribers' plants are estimated on an annual charge basis for various distributions of the loss between the two types of plant. The transmission losses are then by successive trial distributed between the subscribers' loops and trunks and the total annual charges are estimated. These estimates will indicate which distribution involves the minimum total annual cost for both plants. This procedure is carried through for each central office in the exchange. The portion of the transmission loss (in T. U.) assigned to the subscribers' loops in each central office area is called the loop limit for that office.

This whole study is, of course, based on an ideal plant in the same manner as in the studies to determine the ultimate number and arrangement of offices in the exchange. Actually, the existing plant may differ materially. After the study is made, therefore, it is necessary to consider the plant actually in service and its effect upon the indications of the study before the limiting loops are finally decided upon.

The preliminary planning of telephone exchange plant has been discussed above largely from an economic standpoint and the discussion may have given the impression that the economics of the problem are given undue consideration. Such is not the case. It is obvious that any construction program must be considered from other angles as well as the economic angles. For example, if one program will result in better service to the public than another program, the program which would result in better service will receive instant and sympathetic consideration, even though this program might not be quite as attractive from an economic standpoint as some other program. Some programs require large amounts of capital, labor, and material, and it is obvious that such programs should be spread out to best advantage over a period of years.

Any program must be considered carefully to be sure that it is thoroughly practicable from a construction and operating standpoint. It is also desirable that all existing plant be used to best advantage, and when such plant is in good condition and would continue to give good service, it is generally desirable that such plant be retained until it has lived a normal life. To do otherwise would use up capital and result in rearrangements and changes which might not be desirable, even though such a course might show some small savings. In all of these considerations, of course, especially those involving rearrangements and changes, the factor of service to the public is given a very prominent place.

It is also important that the plans for the future extension of the plant be developed in a manner that will permit of a maximum of flexibility in caring for the future service requirements. Thus the characteristics of a plan must be such that suitable adjustments can be made economically in the event that the growth performance in the future varies materially from that upon which the plan was based. In other words, before commitments are made in line with any future plan, this plan is considered broadly from all angles and advantage taken of the knowledge and experience gained in the execution of similar plans.

It is hoped that the preceding outline of the broad general considerations of planning, together with the earlier outline of some of the economic features, will accomplish the purpose of this paper, which as previously stated is to give a general idea of the methods used in planning telephone exchange plants.

## Discussion

**E. N. Widen:** In discussing Mr. Stephenson's paper, I will confine myself to only one of the important questions upon which it touches, namely, the importance of population forecasting. People constitute the telephone market; therefore, forecasts of the future growth in the telephone market of a community must be based upon a consideration of the probable changes in the number and character of its inhabitants. In the telephone business, the importance of forecasting the future demand for service can hardly be overemphasized for two reasons: first, an obligation rests upon a telephone company to deliver service when and where it is needed; second, sound population forecasts are essential if the losses incident to over-built or under-built exchanges are to be avoided.

The telephone plant, especially in large communities, is each year becoming less susceptible as a whole to radical changes in basic plans, a fact which further emphasizes the importance of appraising the future market carefully. Other utilities, including electric light and power companies, gas companies, and street railways, are faced with practically the same problem in estimating their future market. Incidentally, the need for population forecasting in city planning might be mentioned, a fact emphasized by the necessity now existing in many of our large cities for costly street-widening projects and the provision of plazas and parks in sections already built.

Business generally, I believe, has become more forward-looking. Manufacturing programs, sales plans, and financing arrangements of large concerns all are based more or less upon forecasts of the volume of business done. However, the importance of forecasting the future volume of business varies widely in different types of industries. A shoe manufacturer, for example, may be utterly mistaken in his ideas of the volume of business to be secured in certain communities; perhaps his expectations are much too high in some instances and much too low in others. Yet, because the manufacturer has no fixed capital investment in the particular communities, such errors in judgment may be of no serious consequences whatever.

Again, if a large distributor finds business below expectations in some of his markets and above expectations in others, he can, with no great inconvenience, concentrate his efforts on the better markets. But the problem is a different one for the telephone company and other utilities. If a city grows far more rapidly than was anticipated, or if its growth comes in unexpected sections, the utilities serving it naturally require a period for planning and installing the facilities necessary to meet the unexpected conditions. In other words, the utilities, with their heavy fixed capital investments, have less flexibility than do most other kinds of industries.

Population forecasting is not a simple undertaking. On the contrary, it requires the most searching analysis of economic resources and economic trends. What most probably will occur to influence population changes is always the first consideration in forecasting the population of a community; sound forecasts cannot be based upon what could or should be done. Moreover, such forecasts cannot be made to rest upon a local point of view. The principal population-supporting activities of a community must be considered from a national and even an international point of view; such procedure ordinarily leads to less optimistic conclusions than those reached by mere local judgment, but they are more likely to be realized.

It must be recognized that cities and regions are in direct competition with each other for shares of the total growth of the country, and that comparative, not absolute advantages are the determining factors. Incidentally, I might mention that the Bell System, in order to improve its population-forecasting work, has undertaken systematic and comprehensive studies of economic changes affecting the number and distribution of the nation's population. As a phase of this work, in the Southwestern Bell Telephone Company, we are making economic surveys of each of the five states in which we operate.

In addition to forecasting the population of a community as a whole, the telephone company has the problem of forecasting the distribution of population within a city. For this purpose it is necessary to consider such questions as transit conditions, probabilities of transit improvements, the availability and desirability of vacant land, and the probable reconstruction and crowding, or perhaps thinning out of population in the older sections. Any forecast of future demand for service requires an appraisal or gradation of the market, with the present and future character of the population assigned to each small area of the city. All this is, of course, essential to the proper layout of the telephone plant. The analysis of the present and future market is likewise fundamental to the proper planning of a sales program.

Everyone recognizes that many uncertainties attend the making of population forecasts. We cannot estimate for accidents nor in long-range forecasting can we estimate for accelerations and delays due to temporary business conditions. Meticulous precision is impossible, but we believe that a working knowledge of conditions in the future is not only a possible and practical thing, but something essential to the intelligent conduct of the telephone business.

**G. J. Vande Steeg:** Mr. Stephenson has stated that it would be unwise from a physical and financial standpoint to undertake a complete conversion in our larger cities from manual to dial-type equipment at one time. Several elements, of course, contribute toward making such a course unwise. One of these is the manufacturing situation and it may be well to discuss briefly some of its aspects.

For the purpose of discussion, we will include, under manufacture, all of the activities in connection with the provision of materials or apparatus, until these are made available to a telephone user. We start, then, with the purchase and assembly of raw materials. This is an extremely important item as the Bell System factories annually require vast quantities of almost all kinds of materials. The yearly requirements for some of the more common and familiar items will indicate the magnitude of this phase of the manufacturer's problem. Among the leading items are steel, 22,000,000 lb.; antimony, 2,000,000 lb.; silk and cotton yarns, 4,000,000 lb.; lumber products, 24,000,000 board ft. The manufacturer of lead-covered cable each year requires 170,000,000 lb. of paper, lead, and copper. Should a complete conversion to dial equipment at one time be found desirable in our larger cities, simultaneous conversions in other large cities in the country might be reasonably expected, resulting in abnormal demands for raw materials with the usual reactions on prices.

The processes of converting raw materials into items useful in the telephone plant are varied and in some cases extremely complex, requiring the services of a personnel ranging from unskilled labor to highly specialized and trained technicians. In the case of dial central-office equipment, the manufacturer installs the equipment. This work requires a force of trained experts and special testing apparatus, to insure satisfactory operation of the equipment when it is turned over to the telephone company.

These points are brought out to indicate the manufacturers' connection with conversion projects so that the desirability of scheduling these projects to insure as nearly as possible a uniform factory load may be apparent. In order to permit the manufacturers to procure raw materials advantageously and to lay out a uniform program of manufacture and training of factory and installation personnel, it is essential that the major conversion projects be scheduled far enough in advance and the program planned to avoid as far as possible excessive peaks in factory loads. Such a program benefits the purchaser in that a better product can be obtained at a lower cost.

It is apparent, I believe, that the manufacturing problems should be given weight in laying out a conversion program. The difficulties and penalties are, however, not controlling and should the desirability of a complete conversion be indicated by thorough consideration of all the factors, the manufacturing difficulties can be overcome.

**H. R. Fritz:** Mr Stephenson, in his paper, referred to loop and trunk studies which are made to determine the economical distribution of the exchange plant between trunks and subscribers' loops in multi-office areas. Such studies assume the use of the most efficient type of subscribers' instruments available at the time. Such an assumption is necessary in order that the most economical use may be made of the cheaper small gage cable.

Continuous improvement has been made in the efficiency of transmitters, receivers, and in the coordinated design of subsets. From time to time, there are made available instruments of such improved efficiency, which are introduced into the plant. The result is that there are now in use several instrument combinations which differ considerably in transmission efficiency. As the limiting loops are established on the basis of using the most efficient type of apparatus, it is obvious that these several types of instruments cannot be used in an indiscriminate manner. To do so and still maintain the necessary transmission standard would mean that the cable plant would have to be designed for the least efficient of the sets.

To avoid this uneconomical procedure and still permit the efficient use of available types of instruments, it is the practise to establish definite zones in each exchange area for the several instrument combinations. Basing these zones on the use of 24-gage cable, the least efficient subsets are restricted to the zone nearest the central office.

The limit of this inner zone is determined by the length of 25-gage cable, which can be used without exceeding the limiting transmission for any particular office. Beyond this limit, a second zone is established, in which subsets of the next higher grade are used. Finally, a third or outer zone requires the use of the most efficient types of instruments. When the limiting loop has been reached with 24-gage in this zone, use is made of combinations of 24- and 22-gage, all 22-gage, combinations of 22 and 19-gage, and finally all 19-gage cable. Loops of such length that the desired transmission cannot be given with 19-gage conductors and the most efficient type of instruments, are given special consideration and the most suitable means for treating them are applied.

This method of zoning instruments permits the maximum and most economical use of the several gages of exchange cable without having to abandon the use of the less efficient subsets. As future improvements in the efficiency of subsets become available, it will be possible to extend the use of small-gage cables, resulting in further economies in the cost of exchange plant.

As mentioned in Mr. Stephenson's paper, the loop and trunk study envisages an ideal plant. The same is true of the instrument zones. Actually, of course, the existing cable plant is not distributed in the manner assumed in establishing limiting loops and laying out the zones. As a rule, there is in the plant a considerably larger amount of 22- and 19-gage cable than required in the ideal plant. This may lead to the temporary establishment of limiting loops and instrument zones different from the ideal. Also, ringing and common battery supervision requirements may modify the use of an ideal cable plant based only on transmission. However, all new plants and additions to existing plants are engineered to conform with the ideal arrangement. Instruments are zoned in the same manner, either on a routine basis or by wholesale changes, depending on circumstances.

# A Thermal Method of Standardizing
## Dielectric Power Loss Measuring Equipment

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***Synopsis.**—After a brief review of the need for reference standards in dielectric power-loss measurements at high voltage and commercial power frequencies, this paper describes a thermal method for measuring dielectric power loss in cable, utilizing the sheath temperature rise associated with the flow of heat due to the power loss within the sheath. Sources of error are discussed briefly, and results are given in comparison with measurements of dielectric power loss by the reflecting astatic electrodynamometer wattmeter using an air capacitor for phase-angle compensation.*

*In connection with the investigation, certain possible errors in dynamometer measurements are noted, particularly the effect of humidity on power loss in the air capacitor.*

### GENERAL

FOR some years, engineers interested in the measurement of dielectric power loss at high voltage and commercial power frequencies, such as in paper-insulated cable, have felt the need for suitable means by which such measurements could be standardized. Until stable standard loads as described by Mr. F. M. Farmer at the Madison Regional Meeting of the Institute in 1926[3] were prepared and circulated among the various laboratories and factories interested, no such reference standards were available. These loads are sufficiently permanent to promise substantial agreement up to 20 kv. among those making dielectric power-loss measurements, which was not the case when cable samples were exchanged for this purpose. It is hoped that similar standard loads will be developed for higher voltages. These, however, are reference standards only. Dielectric power-loss measurements should be standardized in terms of well established units if possible.

It is considered that a check on dielectric power loss may be made with considerable accuracy by examining the heat appearing in the dielectric under consideration. The methods that occur to one as promising are either (1) a flow calorimeter or (2) the comparison of surface temperature rise of two samples under similar conditions,—one having dielectric power loss; the other, a source of heat easily measured with the desired accuracy, such as d-c. ohmic power loss in the conductor. When the temperature rises are equal, the dielectric power loss in the former is taken equal to the ohmic power loss in the latter. The symmetrical geometry of lead sheathed cable and the ease of making measurements on a short section of a long cable (thus avoiding end effects), led to the adoption of the latter method which will be known in this paper as "comparison of heating." Results of preliminary measurements by comparison of heating at about 35 kv. three-phase were presented by Mr. E. S. Lee in the discussion of the Symposium on Dielectrics and Power Factor Measurements held at the Niagara Falls Regional Meeting of the Institute in 1926.[4] The present investigation extends this method to single-phase measurements at 90 kv., and introduces refinements in the apparatus and method.

It should be noted that our immediate interest in this work was the detection of any constant error in the dynamometer wattmeter equipment as used for the measurement of dielectric power loss in high-voltage cable.[5] Due to this interest, several other phenomena not closely connected with the thermal measurement of dielectric power loss, especially the fairly definite loss in the air capacitor at high relative humidity, were examined and are reported here.

This paper is presented that others interested in dielectric power-loss measurements at high-voltage and commercial power frequencies may avail themselves of our experiences with this method as a means of checking dielectric power-loss measuring equipment.

### DESCRIPTION OF APPARATUS

Comparison of heating requires the measurement of the ohmic power loss in the conductor of one cable which produces nearly the same sheath temperature rise as that of a similar cable to which alternating voltage is applied across the insulation, the cables being under like conditions for heat flow to the surrounding medium; that is, two like cable samples with suitable terminals are required, mounted in some medium that provides approximately constant ambient temperature and like conditions for heat flow from the two cables. Means must be provided for the measurement with necessary accuracy of the small temperature difference between the two sheaths. Actual temperature rises are not needed if the condition of constant equal ambient temperature and thermal emissivities constant in time can be maintained. Air is not necessarily the best medium of those suggested to meet these conditions, but it was found quite satisfactory in the apparatus described below.

A room with thermostatically-controlled heaters was available for the test. With the thermostat set for 33 deg. cent., and the air in the laboratory at about 27 deg. cent., (normal summer condition), the air in the lower part of the room went through cycles of about 20-min. duration with a maximum temperature difference of 0.6 deg. cent. The average temperature of the various cycles varied through a range not exceeding 0.1 deg. cent. with the latter part of the day usually a few hundredths of a degree hotter. In this room were placed two 30-ft. (9.2-m.) lengths of 750,000-cir. mil (380 sq. mm.) stranded-conductor lead-sheathed cable, insulated with 0.750-in. (19 mm.) oil treated paper; 10-ft. (3.05 m.) measuring sections at the middle of each length were insulated by cutting out about ⅜ in. (0.9 cm.) of lead and filling the space with gum rubber. These measuring sections were supported near the floor (Fig. 1) and enclosed in a tight paper box. This paper box (shown with the top rolled back in the figure) served to reduce the cyclic variation of ambient temperature from 0.6 deg. cent. to less than 0.2 deg. cent. The cable ends were carried up to suitable terminals on the roof and the sheaths beyond the measuring section, together with a network of piping and low-voltage wiring conduit on the ceiling, carefully grounded, thus providing electrostatic shielding of the measuring section.

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[3] See Bibliography.

*Presented at the Regional Meeting of the A. I. E. E., District No. 2, Baltimore, Md., April 17-19, 1928.*

Fig. 1—Cable Samples Arranged for Dielectric Power Loss Measurement by Comparison of Heating

Two schemes of temperature measurements were used. Four sets of thermopiles, each consisting of 20 copper ideal junctions in series, 10 "hot" junctions embedded in the sheath of one cable and 10 "cold" junctions in the other, were distributed along the measuring sections of the cables to permit reading temperature differences. The second scheme consisted of five resistance temperature detectors made of 10-mil (0.065 sq. mm.) enameled copper wire wound in contact with the sheath of each cable and covered with a strip of 0.010-in. (0.25 mm.) horn fiber. The thermopile e. m. fs. were obtained from observation of the deflection of a galvanometer of suitable sensitivity in series, taking deflection in both directions.

A potentiometer was used to measure resistance temperature detector resistances. It appeared to have some advantage over a bridge for the low-resistance (10 ohms) detector used.

Direct current was circulated through the conductor of one cable from a motor-generator run from a "constant voltage" supply, with manual control to supplement the voltage regulator. The power dissipated in the cable conductor was measured with portable ammeter and millivoltmeter carefully calibrated. Alternating high voltage of 60-cycle frequency was impressed on the other cable from a 70-kv-a. testing transformer supplied from a generator of good wave form. Voltage measurement was by means of a portable dynamometer type voltmeter connected to the voltmeter coil of the testing transformer and checked against the potential transformer and voltmeter of the dielectric power loss dynamometer wattmeter equipment.

## HEAT FLOW

Two questions may well arise here concerning the necessity for approximately constant ambient temperature and the possibility of error due to axial flow of heat along the conductor. Constant ambient temperature is necessary because the dielectric power loss in paper-insulated cables at a given voltage changes with temperature and because, of the two cables, the one heated by dielectric power loss will respond more rapidly to changes in ambient temperature than the one heated by copper loss. Fig. 2, showing temperature difference as a function of time between two cables having dielectric power loss in one very slightly less than the ohmic power loss in the conductor of the other, illustrates this.

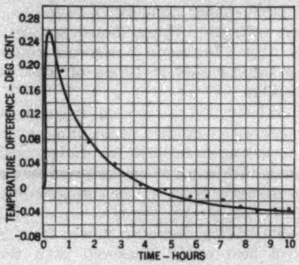

Fig. 2—Temperature Difference between Cable Sheaths as a Function of Time

Ordinate is temperature of cable sheath *A* minus temperature of cable sheath *B*, with dielectric power loss in cable *A* nearly equal to ohmic loss in conductor of cable *B*

The possibility of error due to axial flow of heat along the conductor may be considered from the standpoint of the following approximate analysis of steady state conditions:

Refer to Fig. 3, which shows a length, $2L$, of single-conductor cable whose axis lies along the x-axis and whose center is at the origin.

$a$ = radius of conductor. (cm.)
$b$ = outer radius of insulation. (cm.)
$\alpha$ = thermal conductivity of conductor (calories per second through a cm. cube per deg. cent. between faces)
$\beta$ = thermal conductivity of insulation. (calories per second through a cm. cube per deg. cent. between faces)
$\theta_1$ = temperature of a point on surface of conductor. (deg. cent.)
$\theta$ = temperature at a point in insulation, coordinates $x, r$. (deg. cent.)
$\rho$ = source of heat, calories per cu. cm. per sec. in conductor.

Neglect radial temperature drop in conductor.

Neglect axial temperature drop in insulation.

Boundary conditions. $\theta = 0$ at $r = b$

$$\theta = \theta_1 = 0 \text{ at } x = L$$

$$\frac{d\ \theta_1}{dx} = 0 \text{ at } x = 0$$

Take a disk element of small thickness $\Delta x$; the flux of heat in the radial direction out of the element[6] equals $\Delta H_r$

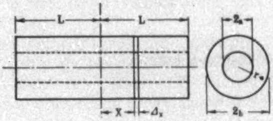

FIG. 3—DIAGRAM FOR AXIAL HEAT FLOW CALCULATIONS

$$\Delta H_r = \frac{2\,\pi\,\beta\,\theta_1}{\log\dfrac{b}{a}}\,\Delta x \qquad \text{(calories per sec.)}$$

The flux of heat in the axial direction out of the element equals $\Delta H_x$.

$$\Delta H_x = -\,\pi\,a^2\,\alpha\,\frac{d^2\,\theta_1}{dx^2}\,\Delta x \qquad \text{(calories per sec.)}$$

Heat appearing in element $= \pi\,a^2\,\rho\,\Delta x$ (calories per sec.)

Then, since the heat leaving the element equals the heat appearing in the element,

$$-\frac{d^2\,\theta_1}{dx^2} + \frac{2}{a^2\left(\log\dfrac{b}{a}\right)}\,\frac{\beta}{\alpha}\,\theta_1 = -\frac{\rho}{\alpha}$$

Solving and substituting boundary conditions

$$\theta_1 = \theta_m\left(1 - \frac{\cosh w\,x}{\cosh w\,L}\right)$$

where $$w = \left(\frac{2}{a^2\left(\log\dfrac{b}{a}\right)}\,\frac{\beta}{\alpha}\right)^{1/2}$$

and $\theta_m$ = temperature of conductor in an infinitely long cable with the same $\rho$ in its conductor; *i. e.*,

$$\theta_m = \frac{\rho\,a^2\log\dfrac{b}{a}}{2\,\beta}$$

In this cable, $w$ = approx. 0.028
$\alpha$ = approx. 1.0 $\quad L = 460$ cm.
$\beta$ = approx. $500 \times 10^{-6}$ $\quad w\,L = 13$

At the end of the measuring section, $x = 152$ cm., and $w\,x = 4.3$

$$\theta_1 = \theta_m\left(1 - \frac{\cosh 4.3}{\cosh 13}\right) = 0.9993\ \theta_m$$

That is, the conductor temperature at the ends of the measuring sections of these cable samples is 0.999 times the temperature that would be reached if there were no axial flow of heat. Thus, for our purpose, flow of heat may be regarded as radial.

### PRECISION OF MEASUREMENT

D-c. power input measurements, as such, call for no further comment. They are of the precision usually obtained with portable instruments and ordinary care. It is necessary to note, however, that, with our equipment, this power input could not be held constant during a heat run as closely as it could be read on the instruments. Momentary departures from the desired value of power input were as great as one and one-half per cent. The same figure holds for departure from the desired value of voltage squared on the cable having dielectric loss. It is believed that over a short period, the mean power was held to within one part in two hundred, though one per cent is reported here as a conservative value for probable error in holding constant power on each cable separately.

Cable charging current, although not entering into the determination of dielectric power loss, was measured, using an electro-dynamometer ammeter with an accuracy of one per cent. The same value of current at a given voltage, obtained from a series of determinations, was used in calculating all power factors at that voltage.

Temperature differences by thermopile were read by a galvanometer. The over-all sensitivity was 0.0015 deg. cent. per mm. deflection. Errors due to thermal e. m. fs. in the galvanometer and series resistance, (used to secure proper damping), were eliminated by reversed readings. Connection to the thermopiles was made by means of copper braid clipped directly to the copper wire leads from the thermopiles. There is here a source of possible thermal e. m. fs. not eliminated by reversed readings. This source of error was investigated and found small as compared with one mm. deflection.

In view of the fact that the resistance temperature detectors were read one at a time, it was necessary to follow a scheme of checking back, reading first a detector on cable $A$, then one on cable $B$, then back again to $A$, in order to avoid errors due to the small cyclic variations in ambient temperature previously mentioned. This variation amounted to about 0.03 deg. cent. at the detectors (0.2 deg. cent. in the air). The sensitivity was about the same as for thermopiles, *i. e.*, readings could be taken quite rapidly to 0.002 deg. cent. Incidentally, the labor of computation is considerably greater with resistance temperature detectors.

Sensitivity of this order, since it was easily obtained, was considered desirable even though it was a little better than the accuracy with which temperature rises could be held; this is, 0.002 deg. cent. represented about 0.001 watt per ft. length of cable, or not over one-fourth of one per cent of the loss in the cable. Control of loss was not quite so close; say, less than one per cent. It is believed that the cyclic variation of ambient temperature led to no constant errors, though it undoubtedly increased the deviation of individual readings from the mean.

Measurements of dielectric power loss on this cable were made with the dynamometer wattmeter measuring equipment under temperature conditions as nearly like those obtaining on comparison of heating as possible. This, together with the close agreement between various dynamometer wattmeter measurements made over a period of five weeks, is believed to eliminate the possibility of serious error due to change in dielectric power loss in the samples. These measurements are recorded in Table I.

TABLE I

DYNAMOMETER WATTMETER MEASUREMENTS OF POWER FACTOR OF CABLES ARRANGED FOR COMPARISON OF HEATING:

Power factor. Cable *A*

| Date | 45 kv. | 60 kv. | 75 kv. | 82.5 kv. | 90 kv. | 100 kv. |
|---|---|---|---|---|---|---|
| 8-2 | $0.0034_0$ | $0.0034_5$ | $0.0035_3$ | .. | .. | .. |
| 8-24 | $0.0032_8$ | $0.0034_0$ | $0.0033_6$ | $0.0033_6$ | $0.0033_6$ | .. |
| 8-25 | $0.0033_6$ | $0.0032_3$ | $0.0033_9$ | $0.0030_8$ | $0.0032_4$ | $0.0034_6$ |
| 9-30 | .. | .. | $0.0032_6$ | $0.0032_5$ | $0.0032_5$ | .. |
| 10-1 | .. | .. | $0.0032_8$ | $0.0032_0$ | $0.0031_8$ | .. |
| | Average | | $0.0033_5$ | $0.0032_2$ | $0.0032_5$ | |

Power factor. Cable *B*

| Date | 45 kv. | 60 kv. | 75 kv. | 82.5 kv. | 90 kv. | 100 kv. |
|---|---|---|---|---|---|---|
| 8-2 | $0.0034_2$ | $0.0031_1$ | $0.0034_2$ | .. | .. | .. |
| 8-24 | $0.0033_4$ | $0.0033_6$ | $0.0034_7$ | $0.0035_2$ | $0.0035_6$ | .. |
| 8-25 | $0.0034_0$ | $0.0033_0$ | $0.0035_8$ | $0.0034_9$ | $0.0035_9$ | $0.0037_6$ |
| 9-30 | .. | .. | $0.0033_2$ | $0.0033_5$ | $0.0033_6$ | .. |
| 10-1 | .. | .. | $0.0032_8$ | $0.0032_8$ | $0.0032_8$ | .. |
| | Average | | $0.0034_1$ | $0.0033_9$ | $0.0034_2$ | |

As a numerical value for error in any one measurement of dielectric power loss by comparison of heating, assume equal weights for one per cent error in holding d-c. power input constant, one per cent error in holding square of impressed voltage constant, and one and one-half per cent error in power corresponding to one-half the cyclic variation of sheath temperature (0.03 deg. cent.)

$$((0.01)^2 + (0.01)^2 + (0.015)^2)^{1/2} = 0.0206$$

or two per cent expected error in final dielectric power-loss measurement. In this cable sample, this is about two-thirds of 0.0001 power factor.

The error in a dynamometer wattmeter measurement, assuming correct phase-angle error compensation, is taken equal to 0.0002 power factor for samples of this size with the dynamometer wattmeter equipment used in this investigation. Thus, a difference between power factor calculated from dielectric power loss by comparison of heating and power factor from dynamometer wattmeter power measurement, greater than 0.0003 power factor, would call for explanation.

## THEORY CONCERNING HEAT EMISSION

Consider two cables, *A* and *B*, set up as described and in thermal equilibrium.

$P$ = loss, watts per cm. length in *A*

$Q$ = loss, watts per cm. length in *B*

$a$ = "thermal emissivity" of *A*, watts per cm. length per deg. cent.

$b$ = "thermal emissivity" of *B*, watts per cm. length per deg. cent.

$\alpha$ = temperature rise *A*, deg. cent.

$\beta$ = temperature rise *B*, deg. cent.

$$\theta = \alpha - \beta$$

$$P = a\,\alpha$$

$$Q = b\,\beta = b\,\alpha - b\,\theta$$

$$Q = P\frac{b}{a} - b\,\theta \qquad (1)$$

or, if $P$ is unknown, $Q$ known,

$$P = Q\,\frac{a}{b} + a\,\theta \qquad (2)$$

$a$ and $b$ may be thought of as somewhat fictitious emissivities invented as a tool for handling quantitatively the consistent small differences in temperature rise that appear when two pieces of cables from the same reel are laid side by side and dissipate equal amounts of power.

These differences would not be expected to be the same for any two sets of temperature detectors applied to the lead sheath but they are considered constant in time if the apparatus is not handled or moved; that is, values of $a$, $b$, and $\theta$ (Equations (1) and (2)) obtained with one set of temperature detectors differ from values obtained with another set of temperature detectors, yet resulting values of $P$ or $Q$ might be approximately the same.

## EXPERIMENTAL RESULTS

Five runs with direct current in each cable were made to provide data for the determination of $a$, $b$, and $\frac{a}{b}$ although only two were necessary to solve for these constants from equations (**1**) or (**2**). The additional runs were made to verify their constancy in time. Results are shown in Table II.

These were followed by six runs, (a "run" referring to the maintenance of a definite current in one cable and voltage on the other cable for the time, about 10 hours, required to reach approximate thermal equilibrium), the results of which are tabulated in Table III.

In this table "th" refers to thermopile determinations. "R. T. D." to resistance temperature detector determination, and "Dyn." to measurement of dielectric power loss by dynamometer wattmeter with air capacitor for compensation. $\theta$ refers to equations (**1**) and (**2**). Note that one run was made on each cable at each voltage as a further precaution against error or change in $a$ and $b$, the thermal emissivities. To aid rapid analysis, power factor results from this table are plotted in Fig. 4.

The two methods agree within nine per cent in any case, or within six per cent for average of all cases. This agreement is at about 0.003 power factor and represents a difference of 0.0002 power factor.

TABLE II
DETERMINATION OF EMISSIVITY
(Symbols refer to equations (1) and (2)

| | | | Thermopiles | | | | Resistance detectors | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Run no. | $P$ | $Q$ | $\theta$ | $a$ | $b$ | $\frac{a}{b}$ | $\theta$ | $a$ | $b$ | $\frac{a}{\theta}$ |
| 1. | 0.0165 | 0.0165 | 0.008 | 0.0144 | 0.0146 | 0.990 | | | | |
| 2. | 0.0165 | 0.0144 | 0.153 | | | | | | | |
| 3. | 0.0129 | 0.0144 | −0.093 | | | | | | | |
| 4. | 0.0155 | 0.0155 | 0.014 | | | | 0.026 | 0.0139 | 0.0142 | 0.980 |
| 5. | 0.0172 | 0.0155 | 0.132 | | | | 0.153 | | | |

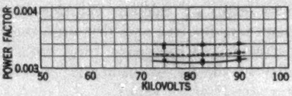

Fig. 4—Graphical Comparison of Power Factor Measurements

- Cable $A$
° Cable $B$

Solid line (————) represents power factor determined from dielectric power loss measurement by comparison of heating.

Broken line (- - - - - - -) represents power factor from dynamometer wattmeter measurement of dielectric power loss

### Application of Results

The comparison of heating measurements were made primarily as a precise check on the dynamometer wattmeter equipment for dielectric power-loss measurement. To make the fullest possible use of this check and to avoid the necessity for frequent repetition of comparison of heating measurements it became desirable that certain possible sources of error in the use of the air capacitor for phase-angle compensation of the dynamometer wattmeter be examined critically and the error reduced to a negligible amount. This work is discussed under two headings: (1) The effect of phase displacement between capacitor charging current and current through the dynamometer wattmeter current coils is under "Review of Compensated Dynamometer Wattmeter Measurement of Dielectric Power Loss," and (2) the fairly definite power loss in the air capacitor at high relative humidity is under "Effect of Humidity on an Air Capacitor."

### Review of Compensated Dynamometer Wattmeter Measurement of Dielectric Power Loss

A brief review of the compensated dynamometer wattmeter method of measurement of dielectric power loss will be of assistance in an examination of the errors which may arise, particularly those associated with high humidity. Fig. 5 shows the connection diagram of the capacitor and measuring circuit described heretofore.[5,7] The guard rings $G$ completely screen the low-voltage plates $B$ from all electric fields other than that from the high-voltage plate $A$. Theoretically $G$ should be at the same potential as $B$. Practically, grounding $G$ introduces no error that can be read, as shown here. If the DPDT switch indicated on the diagram is thrown to position $M$, capacitor charging current less that part of it shunted through the capacitance and leakage resistance (see Fig. 6), from low-voltage plate to ground flows through the current coils of dynamometer $D$. Then $Z_p$ may be adjusted in phase angle for zero deflection of the dynamometer, indicating a 90-deg. phase angle between dynamometer potential coil current and dynamometer current coil current. This will also indicate a 90-deg. phase angle between dynamometer potential coil current and the charging current of a pure capacitance if the air capacitor $A$-$B$ has negligible loss, the capacitance $B$-$G$ from low-voltage plates to guard ring is negligibly small and the leakage resistance $R$ from low-voltage plates to guard ring is sufficiently high. If $R$ is large compared to the impedance of the dynamometer wattmeter current coils, $R_c + X_c$, the phase difference between currents $I_1$, and $I_c$, Fig. 6, may be regarded as $X_c/R$.

The minimum value found by measurement for $R$ is 50 megohms. This observed value occurred at 70 per cent relative humidity and 26.5 deg. cent. The dynamometer wattmeter current coil reactance, $X_c$, is 93.5 ohms at 60 cycles.

$$\text{Phase difference} = \frac{X_c}{R} = \frac{93.5}{50 \times 10^6} = 0.000002.$$

Making the usual assumption concerning very small angles that the angle, its sine, and its tangent, are all equal, this is a power factor error of 0.000002, which is clearly negligible as compared with 0.0002 power factor measurable with the dynamometer wattmeter equipment.

The capacitance $B$-$G$ from low-voltage plate to guard ring, including leads, is approximately 1300 $\mu\mu$f. or 2-megohms reactance at 60 cycles. Dynamometer wattmeter current coil resistance, $R_c$, is 162 ohms. The phase difference between currents $I$ and $I_1$ is then approximately

$$\frac{162}{2\times 10^6} = 0.00008$$

This is a power-factor error of less than 0.0001, which is nearly significant but not large enough to read on the dynamometer wattmeter. Note that a similar phase displacement in the same direction occurs when the cable sample is connected to the dynamometer wattmeter. With ordinary guard ring construction, the capacitance from sheath to ground is usually smaller than that from low plate to ground of the air capacitor; thus, it tends to reduce the total error. Special tests must be watched carefully to see that this capacitance does not exceed reasonable values, say twice that from low plate to ground of the air capacitor.

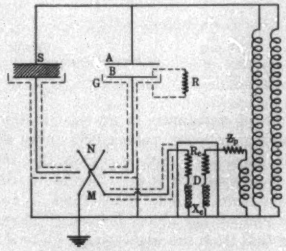

Fig. 5—Connection Diagram of Dielectric Power Loss Measuring Apparatus

$S$ Sample to be measured
$A$ High-tension plate of air capacitor
$B$ Low-tension plate of air capacitor
$G$ Guard ring and lead shielding
$R$ Leakage resistance from $B$ to $G$
$D$ Reflecting astatic electrodynamometer wattmeter
$Z_p$ Impedance of wattmeter potential circuit
$R_c$ Resistance of wattmeter current coils
$X_c$ Reactance of wattmeter current coils

## Effect of Humidity on an Air Capacitor

Observation of the performance of several high-voltage air capacitors used for dielectric power-loss measurement shows occasional conflicting results on damp summer days. These cases of suspected error, although infrequent, make all dielectric power-loss measurements in terms of an air capacitor subject to doubt until the conditions associated with them can be stated. An examination of the technical literature fails to show that such doubtful readings have been ascribed to actual power loss in very humid air, but in each such case, humidity probably varied to a greater extent than did other conditions. Hence, it seemed well to investigate the effect of humidity on an air capacitor used for phase-angle compensation of the dynamometer wattmeter for dielectric power-loss measurement.

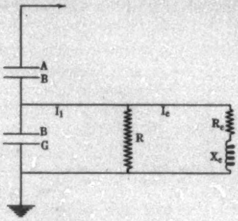

Fig. 6—Equivalent Circuit, Air Capacitor, and Instrument

While the comparison of heating measurements were under way, such an air capacitor, as described in detail elsewhere, was enclosed in a tight box equipped with means for controlling and measuring humidity. Humidity was increased by slowly introducing water vapor into a circulating air stream within the box or decreased by exposing calcium chloride in the box. Measurement was by wet and dry bulb thermometer in the air stream. In each case, time was allowed for the humidity of the air between the capacitor plates to assume a steady-state value.

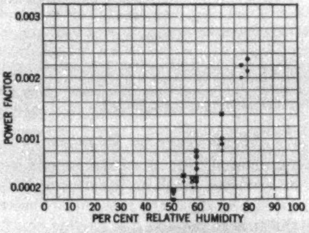

Fig. 7—Power Factor of Air Capacitor as a Function of Relative Humidity

. 50 kv. 60 cycles applied
° 70 kv. 60 cycles applied
□ 90 kv. 60 cycles applied
Air temperature 25 deg. cent.

The capacitor was used at various relative humidities and temperatures to compensate the dynamometer wattmeter for measurement of the apparent dielectric power loss and power factor of the cables previously standardized by comparison of heating. The power factor of either of these cables as measured repeatedly by dynamometer wattmeter with the air in the capaci-

TABLE III

DIELECTRIC POWER LOSS IN CABLE BY COMPARISON OF HEATING, COMPARED WITH DYNAMOMETER WATTMETER MEASUREMENT

| Ohmic loss in conductor watts per cm. | Sheath temperature difference $\theta$, deg. cent. | | Voltage applied to: | | Dielectric power loss. Watts per cm. | | | *Power factor | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | By comparison of heating | | | | |
| | by th. | by R. T. D. | Cable | Kv. | Th. | R. T. D. | By dyn. | By comparison of heating | By dyn. |
| 0.0155 | 0.096 | 0.117 | *B* | 75 | 0.0142 | 0.0142 | 0.0154 | $0.0031_3$ | $0.0034_1$ |
| 0.0144 | −0.008 | 0.021 | *A* | 75 | 0.0142 | 0.0143 | 0.0152 | $0.0031_4$ | $0.0033_5$ |
| 0.0182 | −0.041 | −0.002 | *A* | 82.5 | 0.0174 | 0.0177 | 0.0180 | $0.0031_6$ | $0.0032_2$ |
| 0.0182 | 0.068 | 0.104 | *B* | 82.5 | 0.0174 | 0.0171 | 0.0189 | $0.0031_0$ | $0.0033_9$ |
| 0.0211 | 0.028 | 0.062 | *B* | 90 | 0.0209 | 0.0207 | 0.0226 | $0.0031_5$ | $0.0034_2$ |
| 0.0211 | −0.003 | 0.028 | *A* | 90 | 0.0209 | 0.0211 | 0.0215 | $0.0031_8$ | $0.0032_5$ |

*Charging current 0.0605, 0.0667, and 0.0732 milliamperes per cm. at 75, 82.5, and 90 kv. respectively.

tor dry was assumed constant. (See Table III and Fig. 4). The difference between the assumed constant power factor and that measured when a given humidity and temperature existed in the air between the capacitor plates was taken as the "power factor" of the air capacitor at that humidity and temperature, indicating an actual power loss between the plates of the capacitor. Results of such measurements are shown plotted on Figs. 7 and 8. Considering the nature of the measurements involved, it is felt that these results are sufficiently consistent to warrant the conclusion that the capacitor is practically without loss below 50 per cent relative humidity, and shows a very marked power loss above 50 per cent relative humidity, larger at greater humidities.

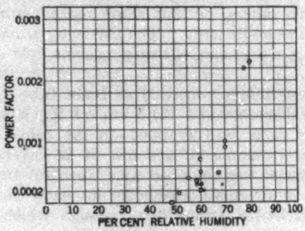

Fig. 8—Power Factor of Air Capacitor as a Function of Relative Humidity

. Air temperature, 20 deg. cent.
° Air temperature, 25 deg. cent.
□ Air temperature, 32 deg. cent.
70 kv. 60 cycles applied to the capacitor

Incidentally, it may be recorded that at high relative humidities, say 70 per cent or 80 per cent, flashover of the capacitor may occur at very low values, as low as 0.7 normal flashover voltage.

No explanation is offered for the observed phenomena beyond a guess concerning charge carried on dust particles. A mixture of permanent gas and unsaturated water vapor was expected to behave as a permanent gas in an electric field. It is believed that the only difference between such a mixture and the dielectric in the capacitor is the probable presence of dust in the capacitor.

### CONCLUSIONS

It is believed that dielectric power loss along two 10-ft. lengths of cable, as arranged for dielectric power-loss measurement in the usual way, has been measured by a thermal method with the accuracy expected from the apparatus employed; *i. e.,* with a probable error not over two per cent. This measurement is at a power factor near 0.003. That the usual electrical measurement of dielectric power loss indicates slightly higher losses, the difference being of the order of magnitude of dynamometer wattmeter reading error, may be either accidental or associated with a small loss concentrated at the end of the measured length, in the ⅜-in. spacing between the measuring section and the guard sections, indicated on the dynamometer wattmeter but missed by the thermal scheme. In either case, it is considered that negligible loss in the air capacitor used with the dynamometer wattmeter is demonstrated, provided that care is taken to keep the relative humidity below 50 per cent in the capacitor. Present practise with this capacitor is the maintenance of relative humidity below 40 per cent.

The thermal method used seems sufficiently simple, accurate, and independent of usual dielectric power-loss measurements, that its occasional use as a check in any laboratory making careful measurements of dielectric power loss is warranted.

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## Discussion

For discussion of this paper see page 836.

# Residual Air and Moisture in Impregnated Paper Insulation—II

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***Synopsis.****—The paper describes further experiments on the drying and impregnating processes of impregnated paper insulation for high-voltage cables. Conclusions are reached as to the relative advantages of drying at atmospheric pressure and under vacuum. The qualities of the product are discussed from the standpoint of conductivity, dielectric absorption, and power factor.*

*The influence of electric stress on impregnated paper and the progressive change in power factor under stress are studied in accelerated overvoltage tests. Evidence is presented as to the nature of certain interesting types of progressive change of power factor in their relation to the amount of residual air.*

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## INTRODUCTION

In an earlier paper[4] we have described a series of studies of the influence of residual air and moisture in impregnated paper insulation, such as used in high-voltage cables. Briefly, the method used was to prepare samples in groups of three, to dry them in accordance with a standard program, to impregnate them at different values of absolute air pressure, and to study the resulting influence on the power factor-voltage curves. This gave information as to the influence of residual air. Separate studies were made of the dielectric absorption and residual conductivity of the paper before and after impregnation for different states of initial dryness. These studies, in conjunction with the resulting power factor-voltage curves, gave information as to the influence of moisture.

One of the conspicuous results of these studies was the relatively small importance of the air pressure, at which impregnation took place, on the resulting power factor-voltage curves. Between one and ten cm. Hg., absolute pressure of evacuation, there was little or no change in the shape of these curves. Moreover they were exceptionally good as compared with the curves of commercial cables, being perfectly flat, up to 300 volts per mil working stress, and for temperatures up to 50 deg. cent. It is only at impregnating pressures above 25 cm. Hg. that the typical rising break in the power factor-voltage curve begins to be evident.

Another result of interest is the relatively small importance of a variation in the moisture content on the shape of the power-factor curve. Moisture content is a relative term, and the foregoing statement refers to variation as regards moisture in a condition which must be described as fairly dry.

## COMPARISON OF DRYING PROCESSES

In view of these results it appeared desirable to study the relative importance of the different drying processes. The inspection of many factories in this country and abroad has shown an extremely wide variation in practise in this regard. The extremes noted were a preliminary drying process at atmospheric pressure, followed by six days under temperature and vacuum, on the one hand, and absence of all preliminary drying, immediate submersion in compound, and 24 hr. heating at reduced pressure on the other. It is obvious, therefore, that either some cables are much better than others, or that some manufacturers are wasting time and energy. The following studies were undertaken in the hopes of throwing some light on these questions:

Each test sample consisted of brass tube 2.54 cm. (1 in.) in diameter, and 121.9 cm. (4 ft.) long. The wood-pulp paper was wrapped on the tubes spirally in the usual manner to a depth of 25 layers. The finished sample was equipped with a central measuring electrode with guard electrode at each side. An electrically heated drying box, through which a slow draft of air is passed, permits drying at atmospheric pressure, and an electrically heated impregnating chamber permits an evacuation down to one mm. Hg., absolute air pressure, before the admission of the compound.

An electrically heated high-voltage test box with suitable electrostatic screening permits measurement of power factor and other alternating quantities, by means of the Schering bridge, up to stresses in the neighborhood of 300 volts per mil. Provision was also made for measuring dielectric absorption and conductivity up to 1500 volts at all stages of the several processes. For further details the earlier paper should be consulted.

In studies of this character it is important to know as closely as possible the state of the paper at the start and at all subsequent times. In drying by elevation of temperature at atmospheric pressure the final steady state of the paper depends on the temperature, the time, and the relative humidity of the atmosphere. Similar samples carried through the same drying process, but at different times, may have widely different residual moisture and electrical properties. It is obvious, therefore, that a standard temperature-

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time program of drying will not result in uniform condition and properties for all samples.

Results presented in the earlier paper trace the behavior of cable paper as regards dielectric absorption and final conductivity, from the initial state when it contains about 10 per cent of moisture by weight, through a drying program which indicates clearly that for temperatures above 90 deg. cent. the conductivity, the dielectric absorption, and the power loss all increase with moisture content. C. Lubben[5] has shown an approximately uniform increase of dielectric absorption with moisture content up to about 5 per cent of moisture. The determination of the absolute amount of water in cable paper is difficult if not impossible, as it continues to give off moisture with increasing temperature, up to destruction. We have preferred therefore to use the conductivity of the paper as an indication of its condition as regards moisture content. The adoption of final conductivity as a standard for the condition of the paper had the advantage that it is a relatively simple matter to adjust the conductivity and hence the relative moisture content to any desired value.

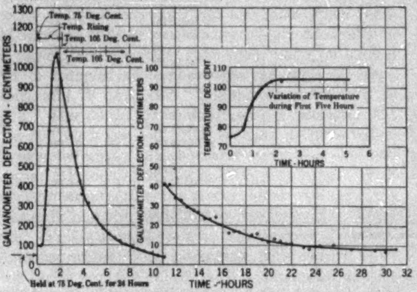

FIG. 1—TYPICAL DRYING CURVE OF UNIMPREGNATED PAPER

Variation of conductivity with time drying in presence of slow draft of air

As a standard condition for the paper we have taken the conductivity which results from a treatment of 105 deg. cent. for 72 hr. at atmospheric pressure in a drying box, through which there is a slow passage of air. In this process the paper reaches a steady state at the end of 48 hr. The change in the conductivity starting from the value of 75 deg. is shown in Fig. 1. The absorption characteristics are shown in Fig. 2. The final conductivity is $0.77 \times 10^{-10}$ mhos per cu. cm. The paper in this condition, therefore, is seen to be an excellent insulator, although possessing high dielectric absorption.

This program of drying and the resulting conditions as described represent the state of best preliminary condition of the paper found in any of our experiments. The current from the test electrode due to the above conductivity, and at 1500 volts, gives a deflection of 3 cm. on a precision galvanometer of sensitivity $2.23 \times 10^{-10}$ amperes. In what follows we shall use the galvanometer deflection directly as a measure of conductivity and moisture content.

In our studies of the relative importance of different periods of initial drying and impregnation, test samples were prepared in groups of three each, with final conductivities in the neighborhood of 30 cm., 60 cm., and 120 cm. galvanometer deflection respectively. The three samples in each group usually differ somewhat amongst themselves and it is therefore not possible to bring all three to the same value of conductivity. We have considered each group of three samples as a unit, treating and drying them together so that the final average values of conductivity are close to the figures mentioned. Specimens having the above characteristics were subjected in turn to evacuation processes represented by 5 cm., 2 cm., 1 cm., and 2 mm. Hg. absolute pressure. Throughout this program the final conductivity at the end of 24 hr. was in general taken as a basis of comparison. Three other groups were also included in this program of tests. No one of these received any preliminary drying and all therefore contained in the neighborhood of eight per cent to ten per cent of moisture. Two of these groups Nos. 28 and 29 were placed immediately in the evacuating chamber and the pressure reduced to 2 mm. Hg., the temperature being held at 105 deg. cent. and the conductivities observed at the end of 12 and 24 hr., respectively. The third group No. 36 was placed immediately in the impregnating chamber, without preliminary drying and the chamber immediately filled with compound. The pressure was reduced to 3 mm. Hg. and the temperature adjusted to 105 deg. cent. and both maintained constant for 24 hr.

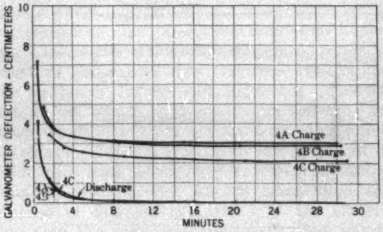

FIG. 2—CHARGE AND DISCHARGE CURVES

Cable paper specimens 4A, 4B, 4C. 1500 volts, 110.6 deg. cent., not impregnated.

Some of the results of these tests are given in Table I. The first column contains the numbers of the groups, each of three specimens. When the same number appears more than once it indicates a continuous run on this group, with observations at the intervals indicated in column 5. Column 2 gives the pressure of

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[5] *Arch. Elek.* 10, 1922, p. 283.

TABLE I

EFFECT UPON CONDUCTIVITY OF COMBINED DRYING AND EVACUATION

All Specimens Dried for 24 Hr. at 105 Deg. Cent. in Air before Evacuating

Conductivity Measurements at 1500 Volts D-c. and 105 Deg. Cent.

| Set No. | Evacuation Press. Hg. | Conductivity at Start | | Reduced to Conductivity of | | |
|---|---|---|---|---|---|---|
| | | Limits | Average of 3 Spec. | Time Interval in Hr. | Limits | Average of 3 Spec. |
| 27 | 2 mm. | 79.00-179.00 cm. | 132.00 cm. | 24 | 2.45- 4.10 | 3.38 cm. |
| 26 | | 9.50- 10.50 | 10.00 | 24 | 2.95- 3.45 | 3.20 |
| 22 | | 3.80- 8.15 | 5.72 | 24 | .50- 5.00 | 2.36 |
| 27 | | 2.45- 4.10 | 3.38 | 36 | 1.35- 2.25 | 1.88 |
| 21 | 1 cm. | 95.00-136.00 | 119.00 | 23 | 7.97-10.57 | 9.15 |
| 25 | | 48.00-125.00 | 80.60 | 23 | 8.20-12.75 | 9.72 |
| 26 | | 25.00- 57.50 | 38.60 | 24 | 10.80-13.00 | 12.25 |
| 22 | | 12.60- 17.80 | 16.30 | 24 | 6.25-12.05 | 8.85 |
| 26 | | 10.80- 13.00 | 12.25 | 24 | 9.50-10.50 | 10.00 |
| 25 | | 8.20- 12.75 | 9.72 | 24 | 8.20-13.20 | 9.93 |
| 21 | | 7.97- 10.57 | 9.15 | 23 | 7.65-10.10 | 8.78 |
| 21 | | 7.65- 10.10 | 8.78 | 23 | 6.75- 9.25 | 7.90 |
| 24 | 5 cm. | 65.00-144.50 | 105.50 | 23 | 15.02-18.77 | 16.64 |
| 23 | | 49.00- 78.00 | 65.80 | 25 | 8.15-11.05 | 9.57 |
| 22 | | 32.50- 34.50 | 33.50 | 24 | 12.00-16.65 | 15.00 |
| 24 | | 15.02- 18.77 | 16.64 | 24 | 11.95-13.70 | 12.88 |
| 24 | | 11.65- 13.25 | 15.76 | 48 | 9.75-13.00 | 11.85 |
| 22 | | 12.00- 16.65 | 15.00 | 24 | 12.60-17.80 | 16.30 |
| 24 | | 11.95- 13.70 | 12.88 | 23 | 11.65-13.25 | 15.76 |
| 23 | | 8.15- 11.05 | 9.57 | 20 | 7.95-11.15 | 9.58 |
| No Preliminary Drying | | | | | | |
| 28 | 3 mm. | Wet | | 12 | 3.00- 3.65 | 3.33 |
| | | 3.00- 3.65 | 3.33 | 12 | 1.75- 2.85 | 2.30 |
| 29 | 3 mm. | Wet | | 12 | 2.70- 3.85 | 3.20 |
| | | 2.70- 3.85 | 3.20 | 12 | 1.80- 2.35 | 2.08 |

evacuation; column 3 the conductivity in cm. galvanometer deflection, the two figures indicating the extremes in the three samples of the respective group; and column 4 the average value of conductivity of the group. Column 5 gives the duration of exposure to the vacuum and column 6 and 7 the conductivities at the ends of the intervals given on column 5. The general arrangement of the table is such as to show continually decreasing values of initial conductivity as shown in column 4, at each pressure of evacuation. Groups 28 and 29, shown at the bottom of the table, receive no preliminary drying and were placed immediately in the evacuating chamber and the pressure reduced to 3 mm. No measurement was made of their initial conductivity and their initial state is described simply as "wet." Group No. 36 was placed in the impregnating compound without any preliminary drying or evacuation. The figures for the initial and final conductivity therefore have no significance in relation to the figures given in Table I. The properties of this group are best understood by a consideration of the power factor–voltage curves. These are shown in Fig. 3 and discussed in a later paragraph.

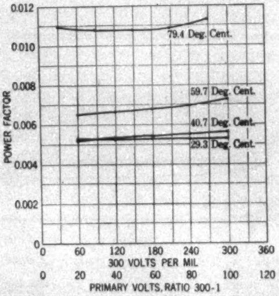


Fig. 3—Power Factor—Voltage Curves

Specimens 36A, 36B, 36C. Conductor diameter = 1.0 in. Insulation = 0.10 in. wall. No preliminary drying

The results as given in Table I indicate that for samples having different values of initial conductivity, corresponding to 30, 60, and 120 cm. galvanometer deflection at 1500 volts, when subjected to 105 deg. cent. and vacua represented by 5 cm., 2 cm., and 1 cm. Hg., absolute air pressure, it is not possible under any length of time to reach the same degree of dryness represented by a sample heated for 48 hr. in a slow draft of air at the same temperature and at atmospheric pressure. The standard value of final conductivity referred to above is approached more and more closely, however, the lower the evacuating pressure.

Evacuation pressures in the neighborhood of 2 or 3 mm. Hg. are necessary if the sample is to be brought down to the standard value of conductivity. Moreover at this pressure and 105 deg. cent. temperature this final conductivity may be reached in 24 hr. regardless of the initial state of the specimen; *i. e.*, a specimen that has had no preliminary drying, and contains therefore in the neighborhood of ten per cent of moisture, may be completely dried in 24 hr. at 2 mm. Hg. and 105 deg. cent. (sets Nos. 28 and 29). Special provision should be made in this case, however, for taking care of the large amount of moisture liberated in the evacuating system.

A freshly prepared sample (group No. 36) having no preliminary drying placed immediately into the impregnating compound at temperature 105 deg. cent. and pressure reduced to 3 mm. Hg. and maintained for a total duration of 24 hr., yields surprisingly good results. The power factor–voltage runs were made on such a series of samples at temperatures 29 deg., 40 deg., 59 deg., and 79 deg. cent. The curves are shown in Fig. 3. The curve at 29 deg. cent. is perfectly flat up to 300 volts per mil, thus showing a curve which compares favorably with our best specimens obtained by other methods of drying and impregnation. With increasing temperature the power factor–voltage curve shows only a slight tendency to rise over the voltage range. This is at variance with the behavior of our best specimens, which with increasing temperature show power factor–voltage curves with a maximum at relatively low stress and thereafter decreasing values of power factor. See Fig. 4. This effect is entirely absent even at 79 deg. cent., in the specimen now under consideration, the power factor–voltage curve at that temperature being approximately flat at low stresses, rising somewhat toward higher stresses. On the whole, however, the curves of set No. 36 show no marked internal ionization and compare well with well dried specimens. The absorption curves taken at 1500 volts continuous potential showed no marked differences.

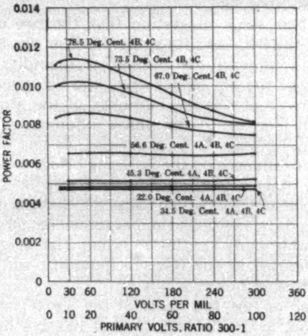


Fig. 4—Power Factor—Voltage Curves

Specimens 4A, 4B, 4C in parallel. Conductor diameter = 1 in. Insulation = 0.10 in. wall. Impregnated at 2 mm. pressure. Conductivity in dried state = 4A—3.40 cm.; 4B—3.45 cm.; 4C—2.55 cm.

It is interesting to speculate as to an explanation of the differences between the curves of Figs. 3 and 4. In the foregoing paper we have traced the intimate relation which exists in impregnated paper between the dielectric loss and the dielectric absorption, as observed under continuous potentials. Moreover, there is much evidence and we are convinced that the phenomenon of dielectric absorption, not only in impregnated paper, but in many other forms of insulation, arises in the conductivity, in the case of paper of the impregnating compound, and in other materials in local paths, due to moisture or other impurities. Now the conductivity of the best grades of insulating liquids is due to the presence of mobile ions in limited numbers. These ions may be swept out at relatively low voltage acting for long periods of time, and more rapidly at higher voltages. In the case of the best impregnated paper, as illustrated in Fig. 4, we may therefore explain the decrease in power factor with increasing potential gradient at the higher temperatures as follows: At the higher temperatures the ions are more mobile and with increasing voltage gradient they are swept out of the field more and more rapidly with consequent reduction in conductivity. At the same time the out-of-phase or charging component of the current increases with the potential gradient, the two effects combining to cause a falling value of power factor with increasing potential gradient. In the case of the curves shown in Fig. 4 relatively moist paper is immediately immersed in the compound. The drying and evacuating under compound leaves some of the moisture in the oil. This has the effect of greatly increasing the number of ions present in the oil and probably in slowing up their mobility. The result is, that with increasing potential gradient conductivity and capacity remain approximately constant, resulting in an almost flat power-factor curve.

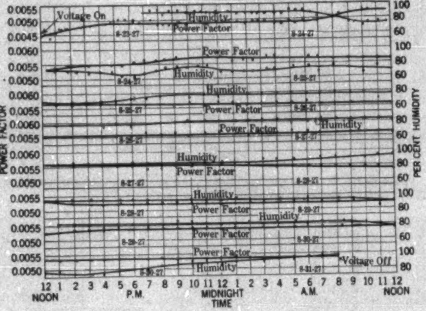
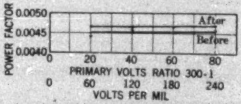


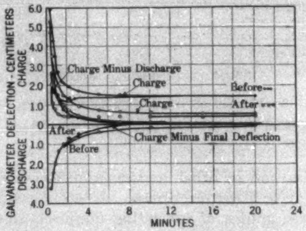
Fig. 5—Variation of Power Factor with Time

Cable specimens 33A, 33B, 33C in parallel. With 12,000 volts, a-c., 60 cycles applied continuously—40 deg. cent.

It is interesting to note that at low temperatures these samples which were dried and impregnated at the same time and with a total time duration of only 24 hr., show power-factor curves comparing very favorably with those of samples, dried, evacuated, and impregnated in separate stages over considerably longer periods of time. At the higher temperatures values of power factor reached are not seriously high. This raises the question whether this short and convenient method of drying results in a poor cable. There is undoubtedly an indication of danger in the rising power factor–voltage curve at higher temperatures. Thoroughly dried and evacuated insulation shows a markedly drooping curve. We attribute the rising curve in the present case to a greatly increased conductivity of the compound, due to moisture. Life tests now in preparation may bring out serious results of these differences.



Power factor—Voltage curves. Before and after specimens were held at 12,000 volts for 190 hr., 60 cycles,—24.2 deg. cent.



Charge and discharge curves, 1500 volts d-c. Before and after specimens were held at 12,000 volts for 190 hr., 60 cycles,—24.2 deg. cent.

FIG. 6—SPECIMENS 33A, 33B, 33C IN PARALLEL. EVACUATED AND IMPREGNATED AT 2 MM.

### CHANGE OF POWER FACTOR WITH TIME

Those accustomed to measuring the power factor of cables and impregnated paper in general have frequently noted that the power factor changes with the time. For the most part, these reported changes are gradual but in a few cases very rapid changes have been reported, as for example, an absolute change of 40 per cent within a few minutes. In our own experiments we have noted changes of a few per cent in observed values from day to day, but for the most part they have not been sufficiently great to require special study nor to affect the general conclusions we have drawn from our studies. The most serious changes of this type we have noted are associated with poorly impregnated specimens at high temperatures. In these cases ascending and descending power factor-voltage curves are separated and variations with time have been noted. Following are the results of further studies in this direction:

One group of samples (No. 33) was dried at 105 deg. cent. and an absolute pressure of 2 mm. Hg. for 24 hr. and then impregnated at approximately this pressure. Power factor–voltage curves were then taken at room temperature (see Fig. 6) and then the temperature was raised to 40 deg. cent. and held constant. The power factor–voltage curve was again taken and all specimens were short circuited and grounded for four hr. The samples were then subjected to 12,000 volts, corresponding to a gradient of 120 volts per mil, continuously for 190 hr. The variation of the power factor during that interval is shown on the accompanying curve No. 5, which shows also the variation of the relative humidity. The value of power factor could be read at intervals as short as two min. When the values were changing frequent observations were made, and always at intervals of at least one hr. It will be noted that during the entire run the maximum variation in power factor was from 0.0045 at the start to 0.0057 on the night of August 24. The final steady value of power factor was 0.0052. The greater part of this difference arises in the first four hr. after the application of voltage, the value reached at this period being 0.0049. The total change during the whole run succeeding this was therefore seen to be relatively small, *i. e.*, 0.0049 to 0.0052.

There was some suggestion that the rise of power factor on the 24th and its gradual fall on the 28th was due to the influence of the relative humidity on the constants of the air condenser of the Schering bridge. If an increase of relative humidity of the atmosphere caused an increase in the phase difference of the air condenser, by leakage or otherwise, as has been suggested, the influence on the Schering bridge would be to lower the observed value of power factor of the specimen. Such an effect would cause the changes indicated in the two days mentioned and as shown on curve No. 5. On the other hand on the 30th and 31st there was a steady increase in the relative humidity without apparent effect on power factor.

In order to test the value of the above mentioned assumption, as to the influence of relative humidity, we made a few preliminary experiments on a small enclosed air condenser in which the humidity of the atmosphere could be controlled. We found that above 80 per cent relative humidity there was an effect of the type mentioned; namely, the conductivity and so the phase difference of the air condenser increased to a value other than zero. Experiments are still in progress to see whether this effect is due to a leakage over the insulation or to some other cause. In the meantime the results obtained have enabled us to correct the few power factor readings which we have found it necessary to take at values of relative humidity above 80 per cent.

At the end of the above mentioned run on group

No. 33, the voltage was interrupted for intervals of one min., five min., and for 30 min., and the power factor measured at the end of each interval. No change in power factor from value 0.0052, at which the original run ended, was observed. In a 20 hr. period without voltage, however, there was a recovery in power factor from 0.00510 to 0.00477. All of these measurements were at temperature of 40 deg. cent. The temperature was then allowed to fall and another power factor-voltage curve taken at room temperature, see Fig. 6. This checked very closely with the original observations indicating that the several series of voltage cycles, the sustained run at 120 volts per mil, and the successive interruptions have not affected the insulation in any permanent way. We conclude from these observations that with well impregnated insulation no sharp and no permanent changes in power factor are to be looked for within a voltage run of 190 hr. at 120 volts per mil.

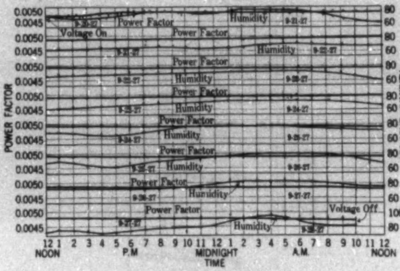
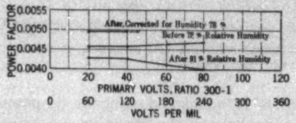


FIG. 7—VARIATION OF POWER FACTOR WITH TIME

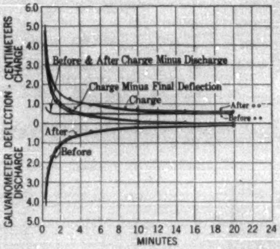
Cable specimens 34A, 34B, 34C in parallel with 12,000 volts, a-c., 60 cycles applied continuously—40 deg. cent.

Measurements were also made of the dielectric absorption and final conductivity at 1500 volts and at atmospheric pressure, before and after the time run described above. The results of these tests are shown in Fig. 6. An interesting feature in these curves is that there was a slight increase in the absorption and a very large decrease (about 60 per cent) in the final conductivity. There is no apparent explanation for this decrease in conductivity. We have noticed this effect in connection with other specimens and it seems to be associated with an initial and temporary condition of the oil following impregnation. It has no apparent influence on power factor observations, as these are determined in large measure by the absorption.

Similar studies as those described for group No. 33 were made with group No. 34, which were dried and evacuated at 2 mm. pressure, but impregnated at 15 cm. pressure. The purpose here was to study the possible influence of a greater proportion of residual air in causing time changes of power factor. The 190 hr. run at 120 volts per mil is shown in Fig. 7, which also gives the curve of changes in relative humidity. It will be noted that there was no abnormal change in power factor. In fact, the power factor remains remarkably constant, beginning and ending at the same value 0.0047, and with a maximum elevation in the intervening period to 0.00495. There is, however, an elevation in the relative humidity above 90 per cent towards the end of the run. Making the corrections on the observed value of power factor in the manner already referred to, the final value of the power factor becomes 0.00495, as indicated in Fig. 8. We therefore found in this group of specimens, as also in group No. 33, a slight increase in the value of power factor as a result of the time run under voltage. There is therefore no evidence here of any marked differences between the specimens impregnated at 2 mm. and at 15 cm. The power factor-voltage curves compared with those for similar specimens reported in the earlier paper are much the same as to both type and values.



Power factor—Voltage curves. Before and after specimens were held at 12,000 volts, 60 cycles for 190 hr.—40.3 deg. cent.



Charge and discharge curves, 1500 volts, d-c. Before and after specimens were held at 12,000 volts, 60 cycles for 190 hr.—40.2 deg. cent.

FIG. 8—SPECIMENS 34A, 34B, 34C IN PARALLEL. EVACUATED AT 3 MM.—IMPREGNATED AT 15 CM.

The absorption showed no marked changes following the 190 hr. run (see Fig. 8).

Group No. 35 was dried and evacuated at 2 mm. pressure and impregnated at 30 cm. pressure. Impregnation at this pressure was known to result in a rising power factor-voltage curve. This group was subjected to the same type of run of 190 hr., at 120 volts per mil and at 40 deg. cent. The results in the power factor are indicated in Fig. 9, which again shows an initial period with rise from 0.0056 to 0.0058 over the first hour and thereafter a slow decrease to a very uniform and steady condition, the testing ending with the value 0.0053, slightly below that at which it started. There were no abnormal elevations of humidity as indicated by the humidity curve, also plotted in Fig. 9.

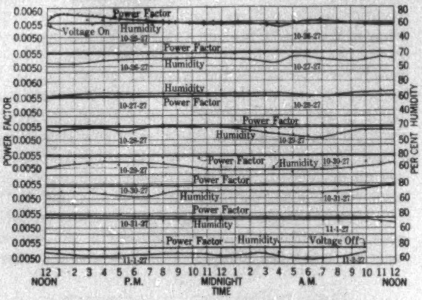
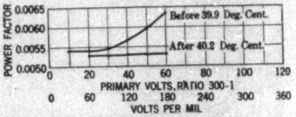


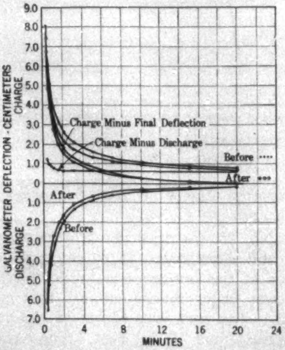
FIG. 9—VARIATION OF POWER FACTOR WITH TIME

Cable specimens 35A, 35B, 35C in parallel with 12,000 volts, a-c., 60 cycles applied continuously

Of particular interest, however, in connection with group No. 35 is the marked change in the power factor-voltage curve between the beginning and the end of this time run. These curves are shown in Fig. 10, and it will be seen that at the beginning there is evidence of pronounced internal ionization, which however seems to disappear as the result of prolonged application of voltage. In the same figure will be found the absorption curves for the beginning and end of the test, indicating a decrease of absorption corresponding to the decreases observed in power factor.



Power factor—Voltage curves. Before and after specimens were held at 12,000 volts, 60 cycles for 190 hr.—39.9-40.2 deg. cent.



Charge and discharge curves, 1500 volts, d-c. Before and after specimens were held at 12,000 volts, 60 cycles for 190 hr.—deg. cent.

FIG. 10—SPECIMENS 35A, 35B, 35C IN PARALLEL. EVACUATED AT 3 MM. IMPREGNATED AT 30 CM.

Two principal explanations suggest themselves for the improvement in the ionization curve of group No. 35 just described. The first of these is a possible improvement in the impregnation due to the fact that in the time runs the specimens are immersed in the compound in which they are impregnated. Although at ordinary temperature and up to 50 deg. this compound is fairly stiff and does not flow readily, it appears possible that there may be a slow change in the degree of impregnation of the samples, over so long a time as 200 hr. The other possible explanation is an influence of the continued application of voltage.

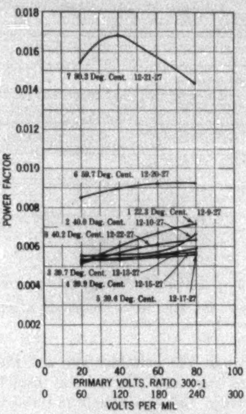


FIG. 11—SPECIMENS 37A, 37B, 37C

Impregnated at 30 cm. Hg. with dried influence of submersion in compound. Curves taken in order 1-8 on dates shown. Voltage applied only during measurements

In order to test the relative importance of these two suggestions an additional group of specimens, group No. 37, was dried and impregnated at 30 cm., giving a group in all respects similar to group No. 35. After the usual process of impregnation, the power factor-voltage curve was taken at atmospheric temperature. The resulting curve is shown as No. 1 in Fig. 11. We then raised the temperature to 40 deg. cent. and power factor-voltage curve No. 2 in Fig. 11 was observed. Voltage was then removed from the specimens and they were allowed to stand in the compound at 40 deg. cent. for a period of 190 hr., voltage being applied only long enough to obtain the power-factor curves Nos. 3, 4, and 5 of Fig. 11. It will be noted therefore that there was an apparent steady improvement in the direction of flattening of the power-factor curve, during this period. At the end of the period, however, the specimens were taken through a temperature cycle up to 80 deg. and on returning to 40 deg. it was seen that the power-factor curve again takes on the ascending shape approximating that of the initial condition. We conclude from these observations that while there is some evidence of improvement of the insulation when standing idle in the compound, it is not a permanent improvement and that after an elevation of temperature the insulation again takes on its original undesirable characteristics.

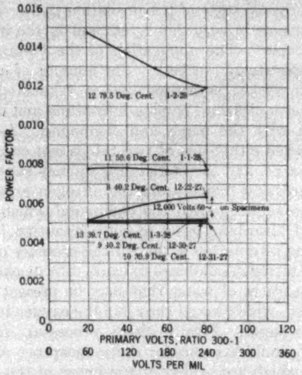


Fig. 12—Specimens 37A, 37B, 37C

Impregnated at 30 cm. Hg. well dried. Influence of continuous application of voltage. Curves taken in order 8-13 on dates shown. 12,000 volts, 60 cycles on specimens for 190 hr. between curves 8-9, at other times voltage on only during measurements

In order to study the influence of the prolonged application of voltage, the same set of samples, No. 37, was next subjected to a run of 190 hr. at 120 volts per mil, at a temperature of 40 deg. cent. The results are shown in Fig. 12, in which curve No. 8 of Fig. 11 is repeated, and the succeeding curves numbered in the order in which they were taken. It will be noted that the 190 hr. run results in a greatly improved, that is, a perfectly horizontal power-factor curve at the end of the run, that a succeeding temperature cycle gives power-factor curves at higher temperatures, similar to those of well impregnated samples, although perhaps a little higher, and that on return to the original temperature of 40 deg. cent. the power-factor curve retains its horizontal position.

The results of the foregoing tests are quite surprising. Although the samples were thoroughly dried they were impregnated at a pressure of 30 cm. Hg. and under these conditions tests, within a period shortly after preparation of specimens, have indicated very undesirable characteristics from the standpoint of ionization. Apparently therefore the insulation is greatly improved by exposure for 190 hr. to a stress of 120 volts per mil. On completion of the foregoing tests all three of the specimens of group No. 37 were dismantled and the paper carefully unwound. It was found that all three of them present all the outward evidences of thorough impregnation, that is to say, the color was uniform throughout and there was entire absence of air pockets or layers. However, on unwrapping samples No. 37 it was found that the paper was noticably drier and more crinkly than that removed from our best type of samples well impregnated at lower pressures. The paper seemed to be drier and actually to have less compound in it.

In order to test these questions still further similar runs were made on a group of samples, No. 42, which contained still more air. In the cases of all the foregoing groups, which were dried before impregnation, this drying was accomplished by subjecting them to a temperature of 105 deg. cent. and absolute pressure, 2 mm. Hg. for a period of 24 hr. They were then allowed to stand for two hr. at the air pressure at which impregnation was to take place, *e. g.*, 30 cm. Hg. in the case of group No. 37. Group No. 42 was dried at 105 deg. cent. in a slow draft of air at atmospheric pressure as already described. The final moisture content as indicated by the conductivity was the same as in group No. 37. They were then impregnated at a pressure of 30 cm. This group, No. 42, was never subjected to an atmospheric pressure lower than 30 cm. It therefore contained more air than the foregoing group No. 37, although both were impregnated at the same pressure. Fig. 13 gives the result of the 190 hr. run at 120 volts per mil and Fig. 14 shows the dielectric absorption and the power factor–voltage curves, both before and after the time run, for group No. 42. The

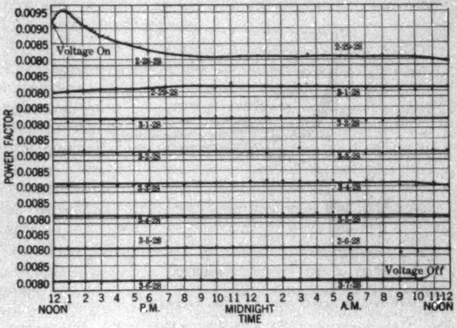
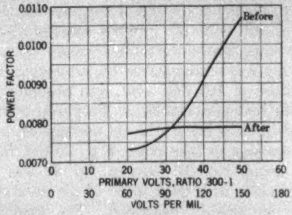
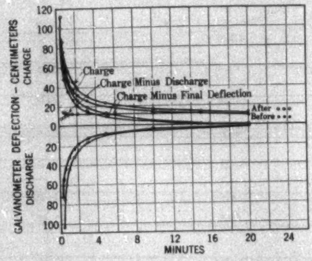


Fig. 13—Variation of Power Factor with Time

Cable specimens 42A, 42B, 42C in parallel with 12,000 volts, a-c., 60 cycles applied continuously—40 deg. cent interesting things to note about these curves are the slight initial rise of power factor at the beginning of the time run, which however, was followed by a noticeably greater decrease during the succeeding eight hr., and the marked changes of the power factor–voltage curve at the end of the time run. The changes in the dielectric absorption are in accord with the changes in power factor. Of these changes the most interesting is the marked improvement in the power factor–voltage curve, as the result of the time run. Before the run this curve rose sharply above 20 volts per mil, indicating copious internal ionization as expected, in view of the large amount of air known to be entrained in the insulation. After the time run, however, this curve became almost flat, lying slightly higher at lower voltage stresses, but rising very little over the remaining voltage range. It appears, therefore, that the improvement noted in connection with group No. 37, resulting from a prolonged run at high voltage, is still more sharply emphasized in the case of group No. 42.



Power factor—Voltage curves. Before and after specimens were held at 12,000 volts, 60 cycles for 190 hr.—40 deg. cent.



Charge and discharge curves, 1500 volts, d-c. Before and after specimens were held at 12,000 volts, 60 cycles for 190 hr.—40 deg. cent.

FIG. 14—SPECIMENS 42A, 42B, 42C IN PARALLEL. EVACUATED AND IMPREGNATED AT 30 CM.

We conclude, therefore, that well dried paper when impregnated at 30 cm. Hg., absolute pressure, has in its initial condition a considerable amount of air and reveals a sharply rising power factor–voltage curve indicating considerable internal ionization. In its earlier stages if left to itself there are progressive changes in the internal condition, as to impregnation, but no permanent change in the undesirable ionization characteristic. On application of voltage there is a steady improvement in the condition of the insulation as regards its ionization characteristic, as indicated by the power factor–voltage curves, and after approximately 200 hr. the insulation reaches an apparently excellent condition with little or no evidence of internal ionization.

In explanation of the foregoing we offer the following: In the original state of the insulation the air exists for the most part in very thin layers and in the interstices of the paper. The application of the voltage ionizes these separate air pockets. The amount of oxygen in each air pocket is limited and is exhausted by the process of ionization, passing into ozone and into combination with the paper and compound. As regards the nitrogen either one of two things can occur. If it is left native, and therefore inert, we may suppose that with increasing temperature the nitrogen expands and goes into solution with the compound which has the power of absorbing gases in some quantity. A more promising alternative is that in the presence of ionization the nitrogen combines to cause nitrous oxides, and with the traces of water that may be present to form nitric acid, which would thus join the oxygen in attacking the paper. Finally these processes, singly or together would account for a disappearance of the air pockets, which are evident if specimens of this type are dismantled in the early stages of their life. The rate of decrease of this disappearance of air is indicated by the curve of Fig. 13 in which it is seen to occur during the first seven or eight hr. after the application of voltage. This explanation would also account for the relatively dry and crinkly appearance of the paper at the end of the run under high stress, and which was very evident in groups No. 37 and No. 42. We attribute this condition to the formation of small amounts of wax or other solid decomposition product which has been frequently noted in connection with over-stressed cable insulation.

The evidence of the foregoing results indicates clearly that the continued application of voltage may result in a marked improvement in the power factor characteristics of impregnated paper, through a consumption or absorption of entrained air, as a result of the process of ionization. An original ionization characteristic is not necessarily a permanent property of this type of insulation.

Another feature of interest in connection with the time runs, described above, is the initial rise in power factor during the first hour or two after the application of voltage. We attribute this rise to the energy liberated within the body of the insulation as the result of dielectric loss. The rise stops as soon as the automatic temperature control equipment readjusts itself to the new rate of energy supplied. Following this initial rise it will be noted that in the cases of samples

No. 35 and No. 42 there is a steady decrease in power factor below the initial value. This decrease is most sharply marked in group No. 42. In the case of these two samples we attribute this steady decrease to the consumption of the entrained air and a consequent lessening of the amount of ionization leading to a decrease in energy loss. The effect is more marked in the case of group No. 42, because that group was known to contain more air originally. One of the authors has already recorded[6] experiments showing the limited amount of oxidation and the gradual change in the nature of the discharge in a thin ionized layer of air, when the layer is completely sealed.

In the earlier paper we have emphasized the close relationship between dielectric absorption and dielectric loss or power factor. The results of the present studies are quite consistent in this regard. In all cases of power-factor changes during the time runs described above, corresponding changes may be observed in the dielectric absorption. The absorption curves, however, were all taken at 1500 continuous volts, which gives a stress far below the alternating values used. Absorption curves for this type of insulation at stresses comparable in value to those of alternating service and tests, are badly needed. In connection with the absorption curves we have plotted the difference between the currents of charge and discharge. This difference shows the irreversible absorption current which is seen to have a considerable value in all the above cases and to rise sharply toward the short time interval, after the application of voltage. This indicates not only the complex character of dielectric absorption as it occurs in impregnated paper, but also that the irreversible absorption current accounts for a substantial portion of the total loss. It is our hope to be able to extend our studies in this direction in the near future.

These studies were carried out in the School of Engineering of The Johns Hopkins University at the request and with the support of the Subcommittee on Impregnated Paper Insulated Cable Research, of the National Electric Light Association, D. W. Roper, Chairman. For the continued interest and hearty cooperation of the members of the committee the authors extend their grateful acknowledgment.

## CONCLUSIONS

Taken in conjunction with the earlier paper our present results would seem to indicate the following:

1. For the drying of cable paper before impregnation, preliminary drying before vacuum treatment is unnecessary, except perhaps as a convenient method of driving off a large part of the water always found in cable paper.

2. Drying at reduced air pressure is very much more rapid than drying in the open, for the same drying temperature. At a drying temperature of 105 deg. cent. at atmospheric pressure, and in a steady draft of air, a steady condition of the paper as regards dryness is reached only after from two to three days. The same condition can be reached if dried at 105 deg. cent. in a vacuum of from two to five mm. Hg. absolute pressure, in from 12 to 24 hr. It is not possible, however, to reach this same condition of dryness over any length of time if the evacuation pressures are above 5 mm. Hg. It is probable that a continuous replacement of water vapor, by dry air in the vacuum chamber, would alter this conclusion. The great value of the draft of air, however, when drying at atmospheric pressure is evident. Higher values of the temperature result in further improvement as regards dryness and conductivity.

Initially undried and unevacuated paper placed immediately in the impregnating chamber and then subjected to heating to 105 deg. cent. and evacuation pressure of 3 mm. Hg. for 24 hr., results in an insulation having remarkably good properties. At temperatures up to 40 deg. or 50 deg. the power factor–voltage curves are flat and of value of the same order of magnitude as those pertaining to specimens that are far more carefully dried. In the upper range of temperatures the power-factor curves have abnormal shapes, although they do not show values unduly high.

4. For thoroughly dried paper impregnated at 105 deg. cent. and pressures of 2 mm., 15 cm., and 30 cm. there are no sharp changes in power factor following abrupt changes of voltage.

5. Prolonged runs under voltage cause no appreciable changes in the properties of thoroughly dried and impregnated insulation (dried at 2 mm. Hg. and impregnated up to 15 cm. Hg.). For insulation impregnated at higher pressures there is a pronounced improvement as a result of the continued application of voltage. We attribute this to the slow consumption of the entrained air in ionization, and its combination with the compound, with resulting decrease in ionization losses.

6. The improvement in power factor noted in the foregoing paragraph is accompanied by a noticeable drying or stiffening of the paper. This we attribute to the production of solid decomposition products of the oil. We thus have the suggestion that the generation of "x-wax," or similar product, is associated with a decrease in power factor. Whether this would continue through long periods is a question for further study.

7. Poorly impregnated cable insulation may show excellent power-factor curves indicating low ionization for temperatures up to 40 deg. or 50 deg. cent. and yet not have permanent characteristics. Examples are group No. 36, impregnated without preliminary drying and showing the curves of Fig. 3, and the several curves around 40 deg. of group No. 37. In such cases a temperature cycle may result in a marked change of characteristics. At higher temperatures there are

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[6] Jl. A. I. E. E., December 1923, p. 1297.

often marked differences from the characteristics of insulation which is thoroughly dried and impregnated.

8. A general survey of these and foregoing studies indicates the relative unimportance of air pressure of impregnation within a fairly wide range say up to 15 cm., and even up to 30 cm., if the paper is vacuum dried. Excellent power factor-voltage curves may be found throughout this range. We conclude therefore that the sharply rising curves and rapid changes in power factor, often noticed in commercial cables are due to relatively large and extended areas of entrapped air or gases, resulting either from imperfect impregnation, distortion in handling, or temperature expansion of lead sheath.

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## Discussion

### DIELECTRICS AND INSULATION

(Scott, Bousman, Benedict, Whitehead, Kouwenhoven, and Hamburger)

Baltimore, Md., April 17, 1928

**W. F. Davidson:** In the paper by Scott, Bousman, and Benedict mention is made of some tests that were conducted to determine the influence on the values obtained of controlling the potential of the guard circuits and in this particular case they found it quite satisfactory to connect the guard circuit to ground. However, in some cases this would not give satisfactory results. I think it is well to caution people working with such measurements to see that they check their own individual circuits.

As a case where serious errors were introduced, I might mention one in which we made a considerable number of measurements at voltages corresponding to a stress of about 250 to 300 volts per mil. In this case we found harmonics in the guard circuit which introduced serious errors in measurement unless they were carried off.

It would seem that the information with regard to the air-capacitor performance (Fig. 7) would be considerably more valuable if stated in terms of stress instead of total voltage applied.

**Donald Bratt:** The consideration of calorimetric methods in dielectric research on high-voltage lead-covered cables confronts us with several interesting problems. The temperature rise on the surface of the cable sheath due to dielectric power loss is significant not only for its average value when taken over a considerable length of cable, but also for its fluctuations over this length.

All our present electrical methods for measuring dielectric power will give only the average value. Now it is well known that a cable which ultimately fails on a high-voltage test gradually develops a "hot spot" at the place of failure long before this failure occurs. It does not seem impossible, therefore, that a study of the steady-state temperature rise whether it be due to dielectric loss alone, to copper loss alone, or to both, could be used as a measure of the *homogeneity* of the insulation.

Let us first take the case of dielectric loss. Assume that a long cable sample subject to high voltage has developed a steady surface temperature rise $\theta = f(x)$ where $f(x)$ is a temperature which may vary over the length of the cable, as measured say from its midpoint ($x = 0$.) In particular, let $f(x) = \theta_1 + \theta_2 E^{-mx_2}$ meaning that in addition to the normal temperature rise $\theta_1$ there adds an amount $\theta_2 e^{-mx_2}$ due to a typical hot spot at $x = 0$ (see Fig. 1 herewith). The question now arises: What conclusions can be drawn from such a temperature curve in regard to the specific loss? It is evident that the sheath must exercise some equalizing influence, so that the variation in losses is more pronounced than exhibited by the surface temperature. Considering the longitudinal heat conduction in the cable as well as the heat dissipation from the cable surface, an expression involving maximum and minimum specific loss is easily derived:

$$\frac{W_{max} - W_{min}}{W_{min}} = \frac{\theta_2}{\theta_1}\left(1 + \frac{2\,m\,\lambda\,a}{T\,S}\right)$$

$W_{max}$ occurs at $x = 0$

$W_{min}$ occurs at $x = \pm\infty$ (meaning *far* from $x = 0$)

$T$ = heat dissipation constant.

$S$ = sheath circumference

$\lambda\,a$ = longitudinal heat conductivity.

Substituting ordinary values for those constants, and assuming $m$ to be $10^{-3}$ per cm² (this would correspond to a temperature decreasing to ½ of its maximum value for $x = \pm 25$ cm.) we obtain

$$\frac{2\,m\,\lambda\,a}{T\,S} = 2.5\,a\,b\,t.$$

and the range of variation is seen to be 1 + 2.5 = 3.5 times as severe as that which would be indicated by the surface temperature.

In view of the recent discussions of thermal breakdown, it would seem to be of great interest to determine the greatest value of $m$ conformal with steady-state performance, as this maximum value undoubtedly reflects the quality of the insulation.

Considering further the question of homogeneity of insulation and the likelihood of a hot spot developing in a region of (let us say) poor heat conductivity, it might be desirable to have a factory test whereby such regions could be detected without even cutting the cable and preparing a sample. Observation of surface temperature rise when the cable is heated,

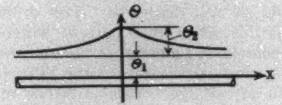

Fig. 1

a. by current in the copper conductor
b. by current in the sheath

leads us immediately to the following conclusions:

1. If the same temperature-rise curve is observed *irrespective* of whether the cable is heated in the copper or the sheath, then the variation in temperature rise must be ascribed to conditions *on the surface*, and the insulation is homogeneous.

2. If the temperature-rise curve differs materially depending on the mode of heating, its variation must, partially or altogether, be ascribed to heterogeneous insulation.

An expression for the equalizing effect of the sheath, on the assumption of constant copper temperature and negligible drop through insulation as compared to drop from surface to ambient air, can easily be derived. We get

$$\theta = \theta_0 + \frac{Q}{t\,A}\left[1 + \frac{E}{\left(1 + \frac{W^2\,h\,\lambda}{T}\right)}\text{Sin. } W\,x\right]$$

where the thermal conductivity of the insulation has been assumed to fluctuate around a mean value with a small amplitude $E$ and a period $x$ where $x = \frac{2\pi}{W}$

The masking effect of the sheath thus manifests itself by cutting the amplitude $E$ down to $\frac{E}{\left(1 + \frac{W^2\,h\,\lambda}{T}\right)}$

Otherwise $\theta$ = temperature at any value $x$

$\theta_0$ = ambient temperature
$T$ = heat dissipation constant
$A$ = total surface of cable sheath
$Q$ = total heat developed in copper
$h$ = thickness of cable sheath
$\lambda$ = lead heat conductivity.

For an ordinary cable, the factor $\frac{W^2 h \lambda}{T}$ would come out about 0.1 so that the equalizing effect of the sheath is not very serious for fluctuations of a reasonably long period. For such fluctuations, therefore, the temperature-rise curve gives a close picture of the variation in thermal conductivity along the cable.

**H. L. Curtis:** In these two papers we have had presented to us some statements regarding air condensers. In one of them the authors have drawn the conclusion that when the humidity is above 40 or 50 per cent there is a loss in the air condenser. The authors of the other paper, I believe, do not get any loss until the humidity is about 80 per cent. In neither case do I think the data are sufficient so that we can judge whether there is a loss in the air itself or whether it is a question of a loss in the solid insulators which support the plates of these air condensers.

**T. S. Taylor:** I should like to ask a question in regard to the construction of the condenser; in particular, is the insulation supporting the plates at all in the field set up by the condenser? Again, is any attempt made to differentiate the factors relative to the losses in the insulation constituting the supports and the conduction losses over the insulating materials?

My experience in measuring power factor at extremely low values such as those of quartz, particularly at high frequencies, has led me to believe that the ordinary type of condenser does not enable us to detect the differences between the components that go to make up the total loss in the condenser. At the present time we have not been able to come to any conclusions as to the distribution of the losses among the various components.

**Alexander Nyman:** I had an opportunity a few years ago to make tests very similar to those described in Dr. Whitehead's paper in connection with impregnated paper condensers, and I am glad to be able to corroborate these tests. Our results were very similar.

In the first place we have to distinguish four factors in connection with impregnated paper condensers. There are the breakdown voltage, the life, the leakage, and the dielectric losses. The leakage is the thing that is most affected by humidity and moreover, by temperature, and the temperature is one factor, I believe, that is not brought out in this paper. We made a number of condensers and put them on long-time tests and observed the relation of leakage current, temperature, and humidity at the same time. We found that the effect of the temperature during the summer months, when the temperature goes up to 80 or 90 deg., was quite marked—more so than humidity. Now those were condensers which were completely impregnated in wax, and yet it seems that the moisture was able to penetrate through the layers of wax and affect the leakage.

Now as regards drying it is exactly as the paper states, you don't have to extract the moisture previous to impregnation. Impregnation, especially if carried out under a vacuum, will extract the moisture. Of course it is a different proposition in manufacturing. In manufacturing it may pay to extract the moisture before impregnation because there may be quite a large amount of moisture trapped and it would prolong the impregnation process too much. But as an actual improvement in the final quality, previous drying is not an important factor.

I should like to say something about what is in my opinion the most important quality in condensers, and presumably cables as well—that is, the life. Of course tests on leakage current and on dielectric losses probably have some bearing on the life, but the relation between these values and the life of the insulating material is not at all evident, and I believe that a much more satisfactory way to predict the life of this material would be to determine by tests—probably very extensive tests—some kind of a law which would connect the life of a condenser with the potential applied to it. Both cable manufacturers and condenser manufacturers have conducted tests of accelerated life at higher than normal voltage, and two or three different laws have been suggested. Cable companies, particularly the British companies, have worked out one kind of logarithmic law to determine the life of a cable at excess voltage. Other laws are slightly different, just the usual power laws. In other words, the life of a condenser will be inversely proportional to a certain power of the voltage. Now these laws will give different results and it is hard to say which is the correct law. This is really a question of great practical importance to both manufacturer and user of every impregnated material. Such material is similar to incandescent lamps or many other electric products which have a definite life; what the life is going to be depends on how severe a service you subject it to.

If you produce a condenser, say, and want to know what is the rating you are going to apply to it, you have to know what the life of the condenser will be before you can decide at what voltage you are going to rate it; in order to determine the life it is either a case of conducting tests for ten years or so, or else applying some law that has to be found by actual tests to be correct. I should like to bring this point to the attention of the investigators.

**A. W. Gray:** I have been much impressed with the fact that apparently no satisfactory explanation has yet been offered to account for the so-called anomalous properties of dielectrics. The various phenomena described by Dr. Whitehead recalled to mind work that had been done in Berlin 25 years ago. I believe that this work gives a clue to a very simple explanation not only of these so-called anomalies, but even of specific inductive capacity.

The work that I refer to was not done upon materials used for electrical insulation, or with any idea at all of elucidating dielectric phenomena; it was done for the purpose of investigating the formation of ozone by the silent electrical discharge in the Siemens ozone generator. This apparatus is essentially a condenser with a composite dielectric consisting of two glass walls separated by a layer of oxygen or of air.

If such a condenser is charged it behaves much as any other condenser behaves until the intensity of the electric field becomes sufficient to break down the insulation of the gas layer and cause a sudden passage of electrons across this layer from one glass plate to the other. This passage is accompanied by a flash of light and by a sudden increase in the charge of the condenser. In addition, there is some comparatively slow passage of electricity from one side of the gas layer to the other by surface leakage along the bounding glass walls. When the composite condenser is discharged by connecting its electrodes together, there is another sudden passage of electrons across the gas layer, in the reverse direction; but this passage ceases when the potential gradient falls to a certain minimum. After this, the discharge continues slowly because of internal leakage around the gas layer. If the electrodes of the condenser are disconnected while the leakage progresses, residual charges on them become evident when they are again connected together.

Every substance, no matter how pure it may be, or how good an insulator it may be, must contain minute spaces distributed among portions that insulate more or less perfectly. These spaces may be bubbles or intermolecular spaces or interatomic spaces or even intra-atomic spaces. The insulating portions may be pictured as forming baffles that intercept electrons shot through the material by the action of an electric field. The conduction current that persists after the field has been established may be pictured as consisting of electrons that succeed in penetrating the baffles and of electrons that are passed on by some procedure analogous to elastic impact. When the substance forms the dielectric of a condenser, the normal currents of charge and discharge may be thought of as arising mainly, if not wholly, from sudden passages of electrons across spaces bounded by layers of baffles. Leakage around these spaces could account for the phenomena associated with dielectric absorption. Such leakage could result from even traces of conducting substances dispersed throughout the dielectric. Since the capacity of such a composite condenser must depend upon the internal structure of its dielectric, it follows that, in general, different substances should be expected to exhibit different specific inductive capacities.

This view conforms to all the essential requirements of Maxwell's theory of heterogeneous dielectrics. For Wagner's artificial assumption of conducting spheres imbedded within a pure dielectric medium without conductivity, it substitutes an internal structure known to exist in every substance. I have not yet learned of any dielectric phenomenon—normal or anomalous—that does not seem to be a natural consequence of actions similar to those observable on a larger scale in a Siemens ozone generator.

An ozone generator can be made to yield information for quantitatively testing deductions from the hypothesis that I have just outlined. For example, electricity passed through the gas layer does work in converting oxygen into ozone and ozone into oxygen. By suitable construction of the generator, internal surface leakage can be rendered negligible, so that the quantity of electricity passed through the gas can be determined from electrical measurements that are fairly easy to carry out. When oxygen flowed through such a generator fast enough to eliminate the de-ozonizing action of the silent electrical discharge, I found, among other things bearing upon dielectric behavior, that the mass of ozone produced was directly proportional to both the quantity of electricity that passed as conduction current through the gas and the difference of potential applied to the electrodes, that is to say, directly proportional to the electrical work done upon the gas. Energy similarly expended upon air occluded within the insulation of a power cable means power-factor loss as well as production of ozone, which should be more active than ordinary oxygen in causing deterioration of the dielectric.

Those interested can look up my original papers.[1] They will find there accounts of such things as the effect of water vapor in the gas and the effect of reducing the suddenness of charge and discharge by inserting a high resistance in the electric path, as well as a description of a method that I devised for using a ballistic galvanometer to measure a single charge, or discharge, while the modified Siemens ozone generator was alternately charged and discharged rapidly at various potentials ranging up to over 12,000 volts.

**J. B. Whitehead:** There has been a number of suggestions from time to time that dielectric absorption arises in the absence of homogeneity of the dielectric itself, and I understand that the suggestion of Dr. Gray is that air spaces through the combination that they offer of leakage paths and also the presence of gaseous ionization, will lead to the ordinary phenomena of dielectric absorption as we know it.

**T. F. Peterson:** One phase of the second paper is particularly interesting to me and I should like to go into it in some detail. To me the results expressed in Figs. 13 and 14 are very striking and indeed, at first thought, seemingly peculiar. They are obtained on what we might consider, in the light of the work done here, poorly impregnated paper, which contains a considerably greater percentage of air than the ordinary samples tested. The explanation offered for the improvement in the power-factor—voltage curve of Fig. 14 seems to be along the right line but probably could be somewhat amplified. The authors have recognized that this rejuvenation of the cable, as we might call it, due to voltage applications, exists, and have accounted for it by saying that the air has either disappeared or has gone into combination with the oil, or something equivalent has taken place. In any event, they claim that it is not due to the entrance of compound from the outside. I do not think that the tests made would warrant forming such a conclusion.

At the Winter Convention of the A. I. E. E. we had a paper by some Russian experimenters on *The Influence of Internal Vacua and Ionization on the Life of Paper Insulated High-Tension Cables*,[2] and in a discussion of it I derived a theoretical power-factor—voltage curve which was very similar to the ones obtained by these experimenters and others. Curve *A B C D* shown herewith in Fig. 2 is typical. At low voltages we have a range of constant power factor. Then, with increase of voltage, a certain stress is reached at which there is an increase in power factor, the curve finally reaching a point where it bends down and becomes negatively sloping. The point at which the increase in power factor takes place is dependent on the thickness of the films at the conductor and also the pressure of the gas. As the voltage increases there is a spreading of the volume of gas in ionization until some point is reached where all spaces are ionized, and then there is a dropping off of the power factor. The curves obtained by plotting the equations which I have derived have been checked up fairly well by experiment.

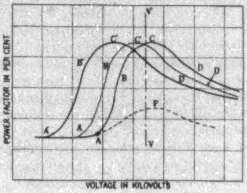

Fig. 2

The point I wish to emphasize is this. Point *A* depends on the pressure of the gas since the value of the stress at which the ionization takes place is proportional to the pressure. Now as the air is absorbed by the compound or is combined in some way with the paper, the pressure will undoubtedly be reduced, and I think to explain fully the characteristics obtained in this paper, we have to consider this. As the pressure changes curve *A B C D* will be moved over to *A′ B′ C′ D′* and we could have a series of curves depending on internal pressures, the lower the pressure the farther left will the curve be.

Now the power factors obtained and plotted in Fig. 13 are for constant voltages. If, with a line plotted through *V V′*, a constant voltage, we consider the power-factor curves moving over with speed proportional to the decrease in pressure and then plot power factor at voltage *V V′* against time we would have a curve such as that given in Fig. 13. This appears to be a partial explanation for the improvement in power factor observed.

In Fig. 14 we have two power-factor curves; one is obtained before any voltage has been applied and is of the characteristic type. It is quite conceivable, due to the slow movement of the compound in cable, that after this application of voltage, the pressure is considerably less than atmospheric. This, in itself, may result in power factor decrease. It may also promote movement of compound into cable which will also assist in this direction. The point at which curve *A B C D* begins to rise is dependent, as I said before, on the pressure in voids and also on the thickness of them. The slope of this curve is dependent on the percentage of these spaces throughout the cable. When the pressure of the gas within the cable is reduced during this test, as the air is combined with the oil, presumably the volume or the percentage volume will remain the same if no compound enters the cable. If compound does enter the cable the characteristics will change and instead of getting curve *A B C D* one would probably get a flatter curve, such as *A P*. In any event, either the reduction in pressure during the test or the entrance of compounds would tend to give us this flat characteristic which is the second one obtained in Fig. 14. Which is the predominating influence is difficult to say because we do not know whether the rate of the reduction of pressure due to the combination of air with the compound is greater than the rate of entrance of the compound. We should have to have some idea of the relative values of those two changes with time before we could say one way or another which was the important influence. I do think, however, that either one can explain the characteristics in some measure.

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[1] "Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften:" *46.* 1016. 1903; *Ann. der Physik: 13.* 447. and *15.* 606. 1904; *Phys. Rev.: 19.* 347. 1904.

[2] See page 731.

**S. J. Rosch**: I believe, after reading this paper, that in presenting the data it has been the intention of the authors to attempt to shed light on some of the obscure fundamentals of dielectric phenomena as occurring in a lead-covered impregnated-paper cable. The cable model as constructed by the authors was an ideal one since the physical relationships between the conductor, insulation, and outer sheath remained constant throughout the experiment, whereas in actual practise the insulated cable receives a number of bending cycles during the various operations before lead covering, and after lead covering during the installation in the ducts, thereby introducing various voids in the insulation proper and between the outer layers of insulation and lead sheath.

Furthermore, for the reasons just mentioned, the electrical characteristics of the cable on the reel in the factory may be entirely different from those obtainable on the cable after pulling through the ducts. Then again, during the entire time when these tests were conducted on the model cable, the latter was completely submerged under oil, a condition entirely foreign to cables as ordinarily manufactured and tested, and only comparable to the conditions accompanying the testing and operation of the oil-filled 132-kv. cables.

However, the data presented in this paper should be of paramount importance to the cable manufacturer, as they indicate an acme of perfection in characteristics not obtainable at present on a commercial scale it is true, but as a desirable goal for the manufacturer to strive to attain in the cables of the future.

I believe, however, that the value of the paper would have been enhanced considerably, if some of the measurements, such as those used to obtain power-factor—voltage curves, could have been continued at temperatures below 29 deg. cent., such as 0 deg. cent.,—10 deg. cent., and — 18 deg. cent., as representing conditions actually met with underground in Chicago and other parts of the country. It would really be of interest to note how the ideal cable would have behaved under these temperatures and whether the compound used would have contracted under the cooling, thereby perhaps causing void formation and producing a different form of ionization curve.

If this research is to be continued, I would suggest that the experiment be repeated but this time using a flexible stranded conductor, the tests being made before and after bending the cable, so as to study effects approaching as nearly as possible those encountered in actual cable practise. I suggest this merely with the thought that a consideration of these parallel data, obtained by the same experimenters, might throw some real additional light on a phase of electrical engineering still woefully obscure.

**G. M. J. Mackay:** Dr. Whitehead's paper emphasizes the fact that in drying cable, applied vacuum simply increases the rate of moisture removal because of the more rapid diffusion of water vapor into the lower ambient pressures. There is no mysterious "pulling out" effect produced by a vacuum pump.

However, it is not quite clear from the paper how the various pressures were maintained. For instance, when a pressure of 5 cm. is specified in Table I, does this mean that the pump was kept running and a constant rate of leak into the apparatus maintained, or that the pump was shut off after a pressure of 5 cm. had been reached? In the latter case, of course, water vapor would not be so thoroughly removed, if at all, and the dryness of the paper would be entirely independent of the pressure of gases other than water vapor itself. Perhaps the relative rate of leak may explain the unexpected improvement found at pressures of 3 mm. Most vacuum pumps do not completely eliminate water vapor from a system because of compression of the vapor to liquid which re-evaporates into the system. Drying agents therefore should be used as near as possible to the material to be dried. The lower the pressure, the more rapid will be the absorption of water vapor by the drier, so that this also may be a factor in the increased rate found at 3 mm.

We have investigated the effect of vacuum on both electrical characteristics and endurance by treating in the laboratory 20-ft. lengths of cable with 9/32-in. insulation, subjecting them to vacuum treatments with pressures varying from 25 mm. to 0.1 mm. and in some instances using liquid air to condense the water vapor. No appreciable difference was found either in characteristics or in life, although these experiments being made with ordinary cable, the effect of such variables may have been masked by the greater effect of voids.

Cable equal in quality to that prepared by the usual methods has also been made by submersion of undried lengths in oil although we have used for this purpose somewhat higher temperatures than those applied by Dr. Whitehead.

We feel that it is decidedly unsafe, however, to carry the conclusion (No. 8) of "the relative unimportance of air pressure of impregnation within a fairly wide range, say up to 15 cm." to the manufacture of long lengths of cable with insulation ¾ in. thick. With the relatively short specimens and thin insulation used by Dr. Whitehead in his experiments comparatively little gas may be trapped. But with a length of cable having insulation ¾ in. thick, impregnation at even 1-cm. pressure may result in undesirable gas pockets. Under the worst condition with compound admitted suddenly and advancing from both ends and the circumference simultaneously, the residual gas at 1/76 atmosphere may be compressed into a single large bubble, which if none escaped, would mean a pocket at atmospheric pressure of 1 ft. in length for every 76 ft. of cable. Either special methods to eliminate this residual gas, or the use of the best vacuum obtainble seems necessary if internal ionization is to be eliminated.

As a matter of fact, oil-filled cable for 132,000 volts is exhausted at pressures always less than 5 mm. and usually below 2 mm.

**W. A. Del Mar:** This work of Dr. Whitehead and his associates is, in my opinion, very valuable and useful to all of us interested in this problem of cable manufacture, because it tells us the properties of a type of cable which must be avoided at all hazards, namely, the perfectly oil-filled cable.

It was my hope and expectation both that the authors would make a perfect cable, not an air-free one, in order that we might have a standard by which we could measure our less perfect commercial products, and that they would ascertain the effect of variations in process upon the quality of the dielectric produced.

The air-free cables made by the authors will probably have zero value from an operating standpoint, if lead-sheathed. If tested under operating conditions of temperature and pressure cycles, I surmise that they will make a very poor record, because the sheath will stretch permanently at high temperatures and high vacua will form at low temperatures, permitting destructive ionization to bring the cables to an untimely end.

The thoughtless will deduce from these tests that the lower the ionization and the higher the dielectric strength, the better the cable This does not follow. In my opinion present-day cables have gone beyond the optimum operating values of these quantities.

The work of Dr. Whitehead and his associates, moreover, seems to come to an end at the point where the really big problems of the manufacturer begin. The big problems of manufacture in impregnation relate principally to dealing with large masses of material and with time limitations. That is to say, one has to consider the movement of air and the movement of oil in large masses, and in the case of the experimental work in this paper those two elements of mass and time are not taken into account. The authors may say, of course, "We stop where you manufacturers should take up the problem," and perhaps that is right, but there are several places in the paper where one would not get that impression. For instance, on the first page occurs the sentence: "The following studies were undertaken in the hopes of throwing some light on these questions," that is to say, the reconciling of two very widely different methods of manufacturing cable. I do not see that experiments on 4-ft. lengths of cable, with the quantities of oil used, throw any light on the relative merits of manufacturing processes.

In order to understand the drying, evacuating, and impregnating processes, the rates of flow of moisture, air, and oil, the masses of water, air, oil, and paper, the nature of the available equipment, and the time commercially available, are the main factors which must be studied. Of course, the authors have not considered these factors, but they have written their paper as if the factors in question are negligible. For instance, it is stated that it is "only at impregnating pressures about 25 cm. Hg. that the typical rising break in the power-factor—voltage curve begins to be evident." This value of 25 cm. is given as a constant, whereas in reality it is only an accidental value depending on the capacity of the particular vacuum pump used in the experiments. In the impregnation process used in these experiments there is a race between the rising oil and escaping air. The authors say that their experiments indicate the air wins the race if the vacuum is better than 25 cm., but they should say that the air wins if the oil does not rise faster than 96 ft. per day, (or whatever the rate may have been) the connection between this rate and the 25-cm. vacuum being dependent on the capacity of the vacuum pump which is sucking up the oil.

I am puzzled by conclusion No.1, which states: "For the drying of cable paper before impregnation, preliminary drying before vacuum treatment is unnecessary, except perhaps as a convenient method of driving off a large part of the water always found in cable paper." Of course, that is the thing we are all trying to do.

No conclusions should be drawn from the experiment on the change of power factor with continued application of voltage until it is studied under more practical conditions, as it is probably a phenomenon peculiar to the test conditions and not to cable in general. If the cable is tested in long lengths, pressure equalization will take so much time that local dielectric heating may cause pressure instead of increased air spaces, thereby giving an entirely different ionization-time curve than obtained on tests of an open 4-ft. length.

I should like to make sure, in places such as Fig. 10, where it says, "impregnated at 30 cm." that that means absolute pressure.

In conclusion I would couple my praise of the excellence of the laboratory work with a caution against drawing conclusions therefrom without giving full consideration to large-scale manufacturing conditions and the modifying effect of temperature and pressure cycles in service.

**W. S. Clark:** The information I am giving comes from the Commonwealth Edison Company. About six months ago they installed some lengths of 132-kv. cable under pressure. They also installed a Schering bridge so that they could make power-factor measurements. There were three or four samples of cable there and I don't know which sample is which except the sample which is oil-filled and which is quite easily distinguished because it is the only one that has shown no change in its electrical characteristics since installation. It comes nearer to what we want as a cable and for cable insulation than anything we have yet had. On the broad question of oil-filled cable—you might say that all cable is oil-filled—but what I mean is cable with reservoirs of oil under pressure,—the use of the ordinary type of cable where the static pressure varies with the temperature of the cable, will have to be worked out on an economical basis. For some voltages it will be advantageous to use an oil-filled cable. For some lower voltages it will be economically better to use the other. But the oil-filled cable so far has done what it was expected to do. In the operating circuits, entirely apart from the circuit I have spoken of, there have been no electrical failures since last June in Chicago and last August in New York, and that includes joints.

**F. M. Clark:** Any discussion concerning the drying of cellulose materials for electrical purposes must define what is meant by the term "dry." In Pittsfield we have found that a sheet of paper may be placed in a 100-deg. cent. oven and dried to a constant weight in approximately 24 hr. If impregnated in this condition the power-factor characteristic will be similar to that described by the authors, yet we do not consider such material dry. Up to this point apparently all that has been done is to remove a large part of the absorbed moisture. To remove more water and to obtain what we term a dry sheet suitable for high-voltage electrical apparatus such as capacitors we have found that a somewhat prolonged vacuum treatment is essential. The actual weight of water removed from the insulation during this stage is not great. The effect on the dielectric characteristics of the insulation, however, is marked, the insulation resistance rising to a high value and power factor dropping well below 0.25 per cent. We believe that in this last stage of the drying process we remove completely all traces of absorbed water together with some water of hydration from the cellulose molecule.

Figs. 3 and 4 illustrate what is termed by the authors as satisfactory behaviour. The effect of voltage on the power factor is absent at low temperature but becomes somewhat more pronounced at higher temperatures. An inspection of Fig. 3 shows that for a constant voltage stress the power-factor—temperature relation varies with the stress applied. At 60 volts per mil, for example, it shows a minimum power factor at approximately 40 deg. cent., whereas at 300 volts per mil the power factor rises rather sharply from room temperature. With Fig. 4, however, the characteristic "V"-shaped curve is obtained at all voltage stresses. It is a characteristic of what we term a well treated dielectric to possess a "V"-shaped power-factor—temperature curve with its minimum value at approximately 35 deg. cent. and a power factor at 50-60 deg. cent which is approximately equal to that shown by the insulation at 25 deg. cent. The authors' curve of Figs. 3 and 4 shows comparatively high power factor at 55-60 deg. cent.

We have in many cases noted a temporary rise in power factor during the early stages of an over-voltage run and have credited it to about the same causes as have the authors—the dissipation of entrapped air or residual traces of water vapor. However, we have not been convinced that ionization is necessary to remove such residual gases. It has been our experience that, even without voltage, gas bubbles trapped in an oil dielectric will disappear in a manner which indicates that the gas is being removed by the process of solution.

The authors in conclusion No. 1 see no reason for a preliminary air brake except as a convenient method for driving off a large part of the water present. As far as I know no one has advocated a preliminary air brake for any other reason. Their conclusion No. 2 states that it is impossible to dry insulation with a pressure of higher than 5 mm. of mercury; yet it is possible to dry in air at atmospheric pressure. It is hard to reconcile such statements unless with the experiments made under 5 mm. of pressure the drying box was tightly sealed in order to hold the pressure constant at this value. Such a static condition cannot be compared with the ordinary conditions present in vacuum treatment where leakage introduces a steady current of air through the treating tank. It is, of course, impossible to dry insulation completely in a "dead" space where a water-vapor equilibrium is soon established between the insulation and the surrounding space.

**G. B. Shanklin:** In regard to the ionization characteristics in the paper by Dr. Whitehead and his associates, from the experience we have had I would attribute the greater part of the unexpected results to the fact that their cable samples were in a bath of compound. We have found that that is the ideal condition; if we could build cable and keep it in a bath of compound we could ask for nothing more. I do not mean, in making this statement, to give the impression that their work is not of extreme value. A fresh point of view and a different way of making the tests is always helpful, but the conditions we have in the actual manufacture of cable, in large vacuum chambers, on large reels, leading those cables and preventing void formation, are really very different from the type of research work which they have conducted. As Mr. Clark pointed out, the liquid oil-filled cable will approach the condition of their research work more closely than a cable filled with heavy compound.

**D. W. Roper:** In Fig. 13 of the paper it will be noted that there is an increase in the power factor with time during the first few minutes following the application of the test voltage. This is the only curve which shows this peculiarity and this curve was taken from a cable sample that was purposely made of poor quality. Professor E. B. Paine, in some investigations that he is making at the University of Illinois, obtained a similar curve from a sample of cable known to be of poor quality that was sent to him for testing purposes. We have recently in Chicago made a life test on a sample of cable showing a similar curve, that is, an increase in the power factor in the first few minutes after the application of the voltage. This test resulted in an unexpectedly short life for the sample of cable as indicated by the other quality tests which had been made in advance of the life test. It is suggested that this point be given careful attention as there is some possibility of this increase in power factor during the first few minutes after the application of the voltage being a more accurate indication of the life of the cable than the actual value of the power factor itself.

**R. W. Atkinson:** I think we have had the first presentation of absolute measurements of the dielectric-loss characteristics of the air condenser, which itself has previously been taken as an absolute standard of capacity and power factor. Now, we have measurements on the air condenser checked against standards even more fundamental. Certain limitations have been shown, in respect to humidity, for the air condenser but it is shown further that, under the usual conditions of use, the air condenser is correctly used as it has been used and is, within the limits stated, an exceedingly satisfactory unit for the purpose.

In the earlier discussions of the paper on residual air and moisture it has been truly said that the measurements are under conditions which are different from those in the factory. It is, however, perhaps this very fact that gives the paper its greatest value. There are already numerous data about the characteristics of cable made under factory conditions. Here we have a set of data about cable made under very carefully controlled conditions, and with these conditions varied in a controlled manner. The application of these conditions, as has been pointed out, is not a matter for an amateur, but it is proper to emphasize that the very real value of this study is due to its uniqueness.

**R. J. Wiseman:** I am going to say only a few words with respect to the cable manufacturer's point of view on the paper of Dr. Whitehead and his associates. I am in agreement with what others have said in regard to the limitations of cable manufacture. There are some points I should like to have considered, not only from the electrical point of view but also from the physical.

Under Conclusion 4, they say "for thoroughly dried paper," etc. We must define "thoroughly dried paper." We can dry paper to the point where it is destroyed and get very good electrical values. However, cables are made to operate for many years. Shall we stop at 0.1 per cent moisture or shall we stop at 0.02 per cent moisture or even go to 0.01 per cent? That is something the cable manufacturer must consider at all times. 0.03 per cent moisture is very readily noticed on the paper by its brittleness. A 0.1 per cent gives good electrical characteristics and longer life. However, the power factor is slightly higher than what we get for 0.03 per cent moisture. Which do we want? From a cable manufacturer's point of view I would say 0.1 per cent if you want to get life out of your cable.

Referring to Figs. 5 and 13, the variation of power factor with time which Mr. Roper has referred to as showing that power factor will vary with time, really is not very great. It is a pretty flat curve from a commercial point of view, only changing 0.05 per cent. It is a good idea to make the ionization test at the beginning and end of a voltage test such as the 24-hr. test we are now making. If the power factor does not show a large increase it can be considered good cable.

With regard to Conclusion 8, I can hardly agree with the statement that:

"We conclude, therefore, that the sharply rising curves and rapid changes in power factor, often noticed in commercial cables, are due to relatively large and extended areas of entrapped air or gases resulting either from imperfect impregnation, distortion in handling, or temperature expansion of the lead sheath."

This may be entirely correct for the rapid changes in power factor but not for the sharply rising curve of power factor, particularly for the higher temperatures. This can be a function of the nature of the compound used. Some use rosin in the compound which gives a slightly increased power factor at higher temperatures, and even at the lower temperatures without rosin you can get a slightly changing power-factor curve. The curve is really a function of the kind of materials used.

**C. L. Kasson:** (by letter) In regard to the paper entitled *A Thermal Method of Standardizing Dielectric Power Loss Equipment*, I should like to point out that no comparison between the values obtained by the thermal and electric methods is correct unless the latter method makes use of electrical shields as well as guards.

Dielectric loss, as usually measured without shielding, includes the loss in the material and the loss in the adjacent air. Under some conditions the watt loss in the adjacent air may be greater than that in the material itself, thus introducing a large error into the unshielded measurements. This was shown in a paper by the writer entitled, *High-Voltage Measurements on Cables and Insulators*,[3] given at Pittsfield, Massachusetts, May 27, 1927, before the A. I. E. E. Regional Meeting.

In order to secure accurate comparisons between the thermal and electrical methods of measuring dielectric loss it will, therefore, be necessary that the electrical measurements be made using a system of complete shielding of the material, its connections, and measuring equipment.

**R. W. Chadbourn:** (communicated after adjournment) Messrs. Scott, Bousman, and Benedict have developed an ingenious and electrically simple method of checking watt-loss measurements on cables. It is unfortunate that the scheme involves such an elaborate set-up and so long a time period to produce steady conditions that its application would be very limited in the laboratory of an operating company—the very place where it might perhaps be of most value.

Considerable care must be taken that the sheath radiation is not affected by external air currents (this requires the use of an enclosed test box of large dimensions), the sheath temperatures must be carefully and accurately determined, and the test must be prolonged over a period of many hours, until the heat flow through the cable reaches a steady state. Because of these considerations, it seems to me that the scheme is chiefly of value to determine, once and for all, for a number of laboratories, the probable accuracy of any direct method of measurement, as with dynamometer wattmeter or the like, or to compare different dielectrics for cable use, where, perhaps, the most accurate possible knowledge of dielectric properties may be important.

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[3] A. I. E. E. Trans., Vol. XLVI, 1927, p. 646.

It should be borne in mind that the measurement of dielectric loss in cables is not, in general, a precision test and that, except in rare cases, a high order of accuracy is not required nor expected. On installed cables, for instance, temperature variations along the cable introduce a variable of such magnitude that accuracy of more than 5 or 10 per cent is, in most cases, impossible. The important thing—in fact, all that can be hoped for—is to be able, by dielectric-loss measurements, to detect cables whose loss is so high that their condition may be definitely questioned, or which show, by a progressive change at given temperature conditions, evidence of gradual deterioration. There are now available, for installed cables, direct methods of measurement, the accuracy of which is known to be entirely satisfactory.

For laboratory measurements involving, in many cases, very short lengths of cables, the temperature variable can be readily eliminated, but this advantage is partly offset by greater difficulties of measurement, due to the smaller quantities measured and the errors introduced by end leakage. The latter can be practically eliminated by proper shielding and guarding, and at the present time portable wattmeters are available for use at very low power factors, of such range that measurements can be made at moderate voltages on lengths of cable as short as 25 or 50 ft., or with some types of cable, 10 ft., with sufficient accuracy for commercial comparisons.

**C. F. Hanson:** (communicated after adjournment) The authors of the paper on *Residual Air and Moisture in Impregnated Paper Insulation*, express a little surprise that Sample Group No. 36, which had no preliminary drying but was immersed in the impregnating oil while the applied paper insulation was at room condition in regard to moisture content, should possess good electrical characteristics. According to my experience, both from the point of view of laboratory performance and that of cable manufacture, I should be disposed to place my wager on Group No. 36 in preference to any of the other groups. I have found that the less the untreated paper is exposed to heat, the better will be the finished product, particularly in regard to dielectric strength. A decrease in the dielectric strength of the oil-impregnated paper due to exposure to heat prior to impregnation will be manifest long before any deterioration can be detected in the physical properties of the paper. If the burden is not too great, I suggest that the authors try to process a group by using a temperature of about 90 deg. cent. or even less in the preliminary and in the vacuum drying. Toward the end of the vacuum-drying period the temperature could be raised to 105 deg. cent. in order to facilitate impregnation when the oil is introduced and also to obtain an impregnating process comparable with that of the other groups.

The authors seem to prefer the power-factor—voltage gradient characteristics shown in Fig. 4 to those shown in Fig. 3. I have noted no data in this paper nor in the authors' previous paper to confirm this preference. I doubt whether anyone at the present time can produce laboratory data which would be conclusive. A laboratory test which will produce unqualified evidence as to the suitability of a cable for service performance is still lacking. Perhaps the best test available now is a long-time voltage test, usually referred to as a life test. I shall await with interest the results of the authors' life test on these various groups.

Below are given data of the power-factor—voltage gradient of two specimens of treated paper. Each specimen consisted of two disks of paper 30 cm. in diameter. These were dried in a current of air at 100 deg. cent. for 72 hr. This temperature was used because no means for vacuum drying were available. The paper was then immersed in the impregnating compound for 18 hr. at 100 deg. cent. under atmospheric pressure. The specimen was then assembled between brass disk electrodes immersed in a pan of the impregnating compound. An attempt was made to remove all visible bubbles of air. There may have been present small invisible air voids due to the method of impregnation. Both specimens were intended to be alike with the exception of the impregnating compound. Specimen A was impregnated with a high-specific-gravity and high-viscosity oil containing 15 per cent of rosin. Specimen B was treated with a mixture of petrolatum and a low-specific-gravity and low-viscosity oil and containing no rosin. It will be noted that specimen A has a power-factor characteristic at 79 deg. cent. similar to Group 36 in Fig. 3. Specimen B has a characteristic similar to that given in Fig. 4. The characteristics of both specimens at 23.5 deg. cent. were flat corresponding to Fig. 3 and Fig. 4.

| Volts per mil 60 cycles | Power factor at 79 deg. cent. Specimen A | Specimen B |
|---|---|---|
| 55 | 0.014 | 0.051 |
| 75 | 0.015 | 0.049 |
| 100 | 0.016 | 0.044 |
| 150 | 0.019 | 0.037 |
| 200 | 0.021 | 0.030 |
| 250 | 0.023 | 0.026 |
| 300 | 0.026 | 0.022 |
| 350 | 0.029 | 0.020 |

These specimens were subjected to a life test with the following results:

| Stress applied 60 cycles Volts per mil. | Temperature 80 deg. cent. Hours application of each stress Specimen A | Specimen B |
|---|---|---|
| 500 | 46 | 46 |
| 600 | 141 | 1.7 Failed |
| 720 | 10.5 Failed | |

The foregoing data are not conclusive by any means but they do suggest that the characteristic of Group No. 36 in Fig. 3 may possibly be preferred to that of Group No. 4 given in Fig. 4.

**W. N. Eddy:** (communicated after adjournment) It is suggested that the authors' first conclusion—that *atmospheric drying* before vacuum treatment is not necessary for the drying of cable paper—is not justified by the data given. Instead, the test results seem to indicate that *vacuum treatment* is not necessary for the drying of cable paper. On the second page of the paper the impression is given that a 3-cm. deflection was obtained after 48 hr. at 105 deg. cent. atmospheric pressure, which is practically as low as any of the deflections obtained in Table I with the aid of vacuum. Also, it should be remembered that pressures below 1 cm. are impractical for factory drying equipment. Table I and Fig. 1 indicate that 24 hr. at atmospheric pressure followed by 24 hr. at 1 cm. pressure (8-12 cm. deflection) did no more complete drying than 30 hr. at atmospheric pressure (8 cm. deflection).

The authors' tests indicate that the pressure and time of drying do not have a controlling influence on the quality of the insulation as shown by the power-factor—voltage curve—in other words, that the presence of some air and moisture in the insulation does not cause increased ionization. The writer is interested in a paper recently completed in which evidence is given that the presence of some air and moisture may actually decrease the ionization, confirming the authors flat power-factor—voltage curves on insulation saturated without previous heating or vacuum treatment.

The general lack of ionization shown by the authors' samples in spite of a wide range in drying conditions is further evidence that the principal cause of excessive ionization and premature failure in high-voltage cable insulation is the formation of contraction voids during cooling, both in the factory tanks and in service. The type of sample and conditions of impregnation and testing used by the authors would indicate that their insulation, as compared with actual high-voltage cable insulation, should be relatively free from such voids and, therefore, of superior quality. To mention another example of the great increase in quality caused by minimizing the formation of contraction voids, cable paper of low air resistance can be impregnated in sheet samples 21 mils thick without previous drying merely by 20-min. immersion in hot compound, so that it will withstand 15,700 volts (750 volts per mil) for 5000 hr. at room temperature. It is thus evident that when working with miniature samples of insulation it is often surprisingly difficult without lowering the saturation temperature to impregnate the insulation so that its quality is anything but satisfactory. As the most desirable method of improving the quality of cable insulation is to study its weaknesses, these characteristics of miniature samples constitute a serious objection to their use.

The authors find no material increase of power factor with time on voltage. Similar results have been obtained with 10-ft. cable samples on overvoltage in the laboratory at room temperature, with the cable ends unsealed. Fig. 3 herewith shows that 5000 hr. of 78 kv. 3-phase on a 3-conductor 33-kv. belted cable under these conditions resulted in a slight decrease in power factor with little change in curve slope. In view of the material increase of power factor often found on cable in service, the constancy of the power factor on the authors' samples and the cable samples suggests that neither test condition approximates actual service conditions closely enough to make the test entirely satisfactory as a criterion of cable insulation quality (its behavior in service). The principal disadvantage of the cable life test may be that the temperature is too uniform and the cable ends not sealed. In addition, the authors' tests have the disadvantage that the insulation is thin.

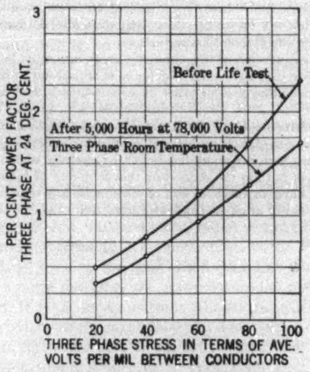

Fig 3.—Power Factor of Three Conductor Belted Cable 33,000 Volts Working Pressure

In general, it is believed that the authors' carefully made and interesting tests offer another example of the great difficulty in applying the conclusions of tests made under typical laboratory conditions to the manufacture and use of actual high-voltage cable insulation. It is becoming more apparent that what have been considered the most reliable indications of insulation quality available in the laboratory, the overvoltage life test and the power-factor—voltage curve, often fail to give a reliable indication of the relative behavior of the insulation in service, and that the principal difficulty is not the nature of the test but the conditions under which it is made. While the relatively constant-temperature, constant-pressure conditions of the laboratory tests tend to decrease the number of contraction voids, the variable-temperature, constant-volume conditions in service tend to increase the number of contraction voids.

**J. A. Scott and H. W. Bousman:** Mr. Davidson's caution about guard-circuit potential is timely. We do not think anyone should either ground his guard circuit or try to raise it to the proper potentials without due care. Particularly this is true with bridge circuits.

Referring to Fig. 7, the capacitor plate spacing is 11 cm.

Mr. Bratt's discussion of heat flow in a cable was very interesting and we hope he will find opportunity to amplify it. For example, we can find no indication that the surface temperature rise of a cable with a "hot spot" is typically a constant plus a normal frequency function, as given by him. There are considerable experimental difficulties with his proposed method for measuring thermal conductivity differences, a measurement which should precede a foot-by-foot comparison of heating test.

How long before failure does a "hot spot" develop?

We may as well admit to Dr. Curtis that so far as we can determine no one has made any conclusive experiments showing appreciably more conduction current in the electric field in moist clean air than in dry air. Our capacitor plates are supported by treated wood carefully kept out of the field, and we were able to repeat the measurements shown in Figs. 7 and 8 over a five-month period. We think there is a conduction current of the order of magnitude shown through the space between the plates. Dr. Kouwenhoven's work with filtered air is in the right direction.

**J. B. Whitehead:** Our point of view in planning the experiments described in the paper has been to isolate, as far as possible, the influence of air and of moisture on the performance of impregnated paper. In order to carry out this isolation it has been necessary to eliminate numerous other factors and conditions which necessarily are present in prevailing methods of manufacturing paper-insulated cables. In other words, we have been studying the fundamental properties of impregnated paper as influenced by air and moisture, quite without reference to the question whether or not it is possible to preserve and protect these properties completely in paper insulation, as assembled in a manufactured cable. The purpose of the investigation has been, therefore, to call attention to the principal differences which obtain between carefully controlled impregnated paper and impregnated paper as it actually functions when applied to a cable. We offer no excuse for this point of view; quite the contrary. We merely call attention to the fact that this is the method adopted in every scientific investigation which aims to uncover the causes of existing troubles. Naturally we shall be more than pleased if manufacturing methods can be improved so that the manufactured cable will approach more nearly the apparently desirable characteristics of some of our specimens.

We believe that many of the comments that have been made on our paper have been made without complete recognition of these facts. We by no means suggest that the processes we have followed in preparing our samples should be followed in manufacture, nor that any of them should be taken as a standard upon which a cable specification might be drawn. We do, however, believe that the relative differences to which we have called attention, among drying processes, impregnating processes, and resulting performance, are in general correct, and can be made use of as bases for changes in manufacturing methods.

For example, some of the comments of Messrs. Del Mar and Mackay have been directed towards possible variations in our results as affected by our methods of evacuating the impregnating chamber and holding the pressure constant. We believe that variations of the character mentioned are quite possible. We do not, however, believe that these variations would be very great. Moreover, as we have followed approximately the same program for all of our samples, we think that the variations so caused would not be great enough to influence the generality of our conclusions.

In direct reply to Dr. Mackay's question the pump was kept running during admission of compound. The rate of admission was adjusted so that the air pressure was maintained at the particular value under test. Departures from this occurred at the higher pressures owing to the limited capacity of the pump.

Answering Mr. Del Mar, the values of pressure are all given in terms of centimeters of mercury absolute pressure.

We have been much interested in Mr. Hanson's preference for the power-factor curves of Fig. 4, over those of Fig. 3, and his suggestion that any sustained heating of the paper, even at moderate temperatures, tends to lower its insulating value. We hope to be able to report in the future on the life tests on these and other types of sample suggested by his comments.

**W. B. Kouwenhoven:** Dr. Curtis has raised a very important question as in both the Schering-bridge and the dynamometer-wattmeter methods of measuring dielectric loss an air capacitor is used in connection with the measuring equipment. It is important for the accuracy of the results that this air capacitor be loss-free.

Scott, Bousman, and Benedict mention the effect of humidity on air capacitors in their paper. During the summer of 1927 troubles which I ascribe to humidity developed in our air capacitor at the Johns Hopkins University. Using continuous potential I made some tests on an air condenser fitted with guard rings and so constructed as to keep the dielectric out of the electrostatic field. The area of the main plate of this condenser is 2260 sq. cm. and the spacing between the plates 2.5 mm. Using this condenser and a continuous potential of 60 volts per mm., I obtained a conduction current of $3.74 \times 10^{-7}$ amperes, at 90 per cent relative humidity. This gives a value of power factor of 0.0008 for the air capacitor under alternating stress and the same voltage gradient as in the continuous-potential tests. It is interesting to note that this value is of the same order of magnitude as that Mr. Hamburger mentioned, as having found during life tests on cable specimens using another air condenser, and that E. S. Lee's results also agree quite closely with this value.

It is very important to know if air capacitors are free from loss or not, and we are studying that question now. We have constructed a special condenser using bakelite as a dielectric which is entirely enclosed and so arranged that air may be circulated through it, and at the same time the relative humidity of the air may be varied. To date all of the tests have been made with clean air (dust-free) and the humidity has been varied from about 40 to 95 per cent. Tests have been made at temperatures ranging from 23 deg. cent. (73 deg. fahr.) to 50 deg. cent. (121 deg. fahr.). In order to keep out the dust a cotton-wool plug is inserted in the air pipe. The value of the applied continuous potential has been varied from 10 to 60 volts per mm. No conduction has been detected with clean air, even at 60 volts per mm., and the following values of relative humidity, 92.5 per cent at 24 deg. cent., 91 per cent at 32 deg. cent., and 90 per cent at 39 deg. cent.

Atmospheric dust in Baltimore contains quite a large percentage of carbon particles, soot, bits of hair, fuzz, dried sputum, bits of dried grass and leaves, etc. One of the next steps in this investigation will be to introduce some dust into the humid air and note its effect upon the conduction.

In an investigation of this character great care must be taken to make sure that any conduction found is not caused by leakage over the insulation or some other unsuspected path, such as a bit of lint.

**J. B. Whitehead:** I think Dr. Kouwenhoven has not been quite definite in stating his belief in connection with the possible rise in power factor of an air condenser. Generally we haven't a great deal of faith in the suggestion that humidity of the atmosphere can have an effect, or can of itself cause any departure of the power factor of an air condenser from zero value.

# Improvements in Insulation for High-Voltage A-C. Generators

BY C. F. HILL[1]
Non-member

*Synopsis.—A discussion is given of the insulation problem in relation to increased size, rating, and voltages of turbo alternators and some results of experimental studies given showing the possibilities of improving the insulation to take care of such increases. Mention is made of the effects of high voltage testing and the use of hydrogen on the insulation problem and finally an explanation of a device for the elimination of corona formed around armature coils.*

* * * * *

THE present type of turbo alternator is the result of but little more than twenty years development but the changes in such machines have been frequent and impressive. The result is that machines are being built so much larger in size and power output than were considered possible a few years ago that we hesitate to predict the future or place a limit on their size. The same condition may become true for voltages as well. However, when we consider the advance in size and rating we are confronted with the fact that much of the change has been made possible by improvements in mechanical features, an outstanding example being the improvement in the method of removal of heat losses. It is true that the magnetic properties of the iron have been much improved and transposition of strands of conductors has helped to lessen eddy current losses, both being examples of electrical advancement, but as each step in the increase in output per unit was necessary, much of the problem was merely increasing the mechanical size. Yet if we could go back to the time when 5000 kw. was considered a large machine, we certainly would not have expected 150,000 kv-a. without almost revolutionary changes by the electrical engineer as well. The demand continues for larger and larger units, especially larger kw. output, and it is difficult to understand how much advance can be made without some improvement in the electrical features. Therefore, the electrical engineer must look for possible changes, in the magnetic circuit, in the generated currents and voltages, and in the insulation. It is the purpose of this paper to discuss the problem of the insulation engineer from the standpoint of increased voltages especially, with some discussion as to the effects of other developments on insulation, and by means of some experimental results to show some of the limits and possibilities which insulation may impose on further developments of turbine design.

## General Discussion

While further increase in voltage will determine the more difficult problem for the insulation engineer, he must keep in mind a number of other features which are to be expected in further turbine development. The mere increase in dimension increases the difficulty of insulating the conductor or coil and placing the coils into the slots in good condition. Armature coils are already of the order of 20 ft. in length in the straight part, and the difficulty of making and handling such coils must necessarily increase with length. Of more importance is the matter of temperature, heat dissipation, and efficiency. The insulation problem has always been tied in with that of temperature and heat removal in that the $I^2 R$ losses in the conductors must be conducted though the insulation and operating temperatures are actually determined by it. The present A. I. E. E. Standards permit, for armature windings, a maximum rise of 80 deg. based on a total temperature of 125 deg. and most large machines are now designed for an armature winding temperature rise of only 60 deg. Only a radical change in the nature and characteristics of insulating materials will permit designers to raise this limit of temperature rise appreciably.

A new development in the field of heat removal may make itself felt in the near future in the way of using lighter gases such as hydrogen for machine ventilation. A trial of this development is now under way and it will therefore be of interest to consider the relation of this method of ventilation to the insulation problem. The aim, of course, is to get increased output at the same temperature, and from this point of view, no effect will be expected on the insulation so far as temperature is concerned. Lighter gases are better conductors of heat and originally there was some hope that even the insulation itself might become a better heat conductor due to absorbed gases. As a matter of fact, an insulation that is good electrically, does not absorb gases to any extent and the only way in which it will be affected by the hydrogen atmosphere involves corona effects which will be mentioned later.

In the case of armature insulation, the development or changes over the past twenty years have been negligible. As a matter of fact, it can almost be said that the idea of arranging paper, mica, and a bond as we have them now, made possible the modern turbo generator. At first, voltages were relatively low and machines comparatively easy to insulate. But even as voltage increased from 2500 to 13,000, the insulation engineer was not handicapped. He has merely maintained an increase in thickness of the dielectric to correspond to the voltage rise. In general the situation as regards turbo insulation is satisfactory; it is true, accidental defects may occur, but periodic voltage tests tend to keep service failures at a minimum and the fact that the insulation engineer has not been handicapped seriously in space allowed, has permitted a fairly large factor of safety to be maintained.

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[1] Research Laboratory, Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

*Presented at Regional Meeting of the A. I. E. E., District No. 2, Baltimore, Md., April 17-19, 1928.*

We are now at the beginning of a further advance in standard voltages as well as kv-a. rating and size of generating units, and the first increase for many years has been proposed from 13,800 to 22,000 volts. On the basis of previous experience and practise a proportional increase in insulation thickness will take care of this change. This being permitted no particular difficulty arises so far as the insulation itself is concerned except to cut down the rate of removal of heat. But it is highly desirable that the insulation carry more of its share of the load in the way of assuming higher working stresses. This thought is not new as the necessity and importance of higher voltage stresses on the insulation in high-voltage applications is already felt but it does call attention to the need of information on what may be expected in the near future in this respect.

The problem has therefore been attacked from the standpoint of a more severe service on the insulation. The starting point of the study has been the weaknesses of the present insulation with a view of determining necessary improvements within the insulation itself but the problem of what may be done outside the insulation to relieve the situation is also considered. Incidentally the effects of one or two other developments on the insulation problem are mentioned.

### MICA FOLIUM UNDER SERVICE CONDITIONS

In order to interpret actual results it will be well to get a clear picture of the insulation studied and the same under service conditions. Mica folium, as it is called, is made of large sheets of paper upon which mica is fastened by means of a bond. The insulation, considered first, is shellac as the bond, holding overlapping mica flakes of two to four sq. in. area. A layer of bond is also placed over the mica surface, and after baking to dryness, the sheet is wrapped around the bar to the desired number of turns and ironed down with heat and pressure until practically a solid insulation is obtained of mica bond and paper. The resultant bars or coils are then wound in the stator slot, a paper slot liner being used to prevent injury to the insulation surface during winding.

Using the shellac bond this insulation has been in use for many years and has given dependable service. Mica of course is a good insulator if it can be held in place and the purpose of the bond and paper is in general to hold the mica although they do have a considerable insulating value. The chief point to be considered with respect to bond and paper is that they be so chosen that they do not detract too much from the insulating value of the mica.

Service conditions in the machine impose heat, voltage, and mechanical vibration effects. Insulation temperatures having been reduced to approximately 100 deg. cent., satisfactory service is obtained so far as temperature is concerned and in general operating voltage stresses in volts per mil have been kept to values allowing a considerable factor of safety. However, in machines with voltages of the order of 5000 or 6000 from conductor to ground, one voltage effect has developed, that of corona, sufficient in strength to remove all organic material with which it comes in contact. The paper slot lining and paper wrapper of the coil may disappear entirely or at least be found to be eaten away in small spots under the corona arcs. After several years service, however, coils have been examined and no effect found on even the first layer of mica; furthermore, beyond the loss of the paper wrapper, no effect on the dielectric strength has been observed.

One of the defects of mica folium has been the slight tendency to swell. The defect has its good point in that it keeps the coil tight in the slot but it was not known just why it swelled or what other features might be introduced. During the present study, most of the cause of this swelling has been definitely proved to be due to a freeing of a slight amount of solvent vapors which, linked with the fact that the insulation is non-porous and tends to retain the vapors, permits the formation of slight internal pressures. By making a porous insulation the vapors could be allowed to escape but it was felt that this would tend to lower the dielectrical strength somewhat which is undesirable. Further studies as to the effect of the swelling confirmed the prediction that the vapor pockets allowed internal corona[2] creating an internal power loss of small amount which add two or three deg. cent. to the insulation temperature. This is not serious at operating voltages but tend to increase faster than the voltage so that at higher voltage gradients it would not be desirable. With this information at hand, coils from machines in service have been examined to see if any internal deterioration of the bond could be detected but none was found. The absence of oxygen accounts for this, the concentration of heat in the arcs being evidently too small to do damage by themselves. One possibility of preventing swelling suggests itself in the way of completely removing all the absorbed solvent before winding the coil; dry shellac has excellent properties but it has not been determined if such is feasible as yet. The work has been directed towards obtaining a bond which lends itself readily to obtaining the desired properties more easily.

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[2] *Gaseous Ionization*, JL. A. I. E. E., Dec. 1923, also TRANS. A. I. E. E., Vol. XLIII, 1924, p. 116.

### Power Losses

In all high-voltage apparatus, an important property of the insulation is that of power losses. By this we have reference to the losses produced by the oscillation of charges within the dielectric itself and manifesting themselves as heat. These have little effect upon the total efficiency of the machine, but although the actual watts lost is not so great, they are concentrated in the dielectric, raising its temperature somewhat. Continued curing by heating tends to lower these losses by removal of more or less volatile material. Solvents would, therefore, be expected to play an important part in the production of these losses and two possibilities suggest themselves in solving the problem. Either to reduce the solvent to a minimum or to use a solvent which has better dielectric properties in itself, or both. The ideal bond would be one which could be melted and applied at temperatures well above operating temperatures, using no solvent whatever. So far the ideal bond has not been found but results show that a large reduction in losses is possible by a choice of bond, having low losses in itself and soluble in a solvent of low loss, with a reduction of this solvent to a negligible quantity in the finished insulation.

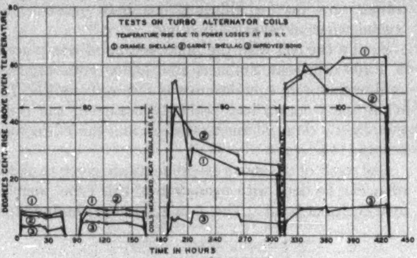

Fig. 1

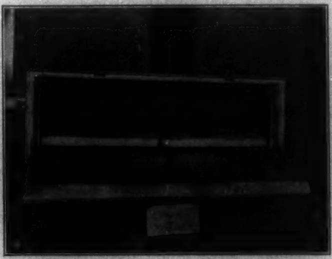

Fig. 2

The curves of Fig. 1 show comparative data on standard mica folium with shellac bond and with a bond recently developed along the lines mentioned above. Since the actual watts loss is of little importance, the temperature rise being of more importance, the temperature rise is used as ordinates in the data. The abscissa is the time in hours that the voltage of 20 kv. is applied to an insulation design for 13,000-volt operation. Attention is called especially to the importance of power losses in case higher voltage stresses are imposed. As a general rule in a 13,000-volt machine, approximately 8000 volts exists across the insulation. More than twice that stress is applied in this case, and it is evident that the losses in the standard folium are too high; on the other hand, the improved bond withstands the voltage readily. Possibly considerably higher temperatures could be used on the latter without sacrificing all the gain over standard folium. The curves also give an idea of the rise in losses with temperature of the insulation.

Fig. 2 is an illustration of the apparatus used in the study of the coils, temperatures being taken by thermocouples inserted in the hollow conductors of the bars. Machine temperatures were imitated by means of a thermostatically controlled oven and the slots by means of metal clamps. Gaps between clamps give the effect of vent ducts, gaps of one-half in., one in., and seven in. being used.

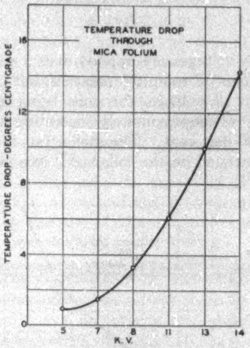

Fig. 3

The curve of Fig. 3 is a characteristic one representing the variation in losses with voltage stress and brings out the fact that the losses increase faster than the voltage. Assuming the equation

$$\text{loss} = E^n$$

$n$ is found to be almost exactly equal to two at 5000 or 6000 volts but increasing gradually to approximately three near the upper end of the curve.

As mentioned above, the swelling of coils due to the solvent is a factor to be considered. Comparative tests on the two bonds in the present case are found in Fig. 4 for a one-half in. gap at 80 and 100 deg. cent. machine temperature. Curve 1 is for a standard shellac folium while No. 2 is that with the new bond. The processing was done in the shop to make the test comparable. It is evident that considerable progress has been made although even a more complete removal of the solvent may be possible. If the surface layers could be preserved as will be discussed later, and the coil originally wound tightly in the slot, the tendency to remain tight rather than loosen is an advantage. A third variation in the power loss studies involves an effect observed when high voltages are applied over a period of time at an ambient of room temperature, but between each application of voltage, the coils being given a heat treatment of approximately operating temperatures around 100 deg. cent. The shellac bond is apparently dry when wound on the coils but it was predicted that some solvent is locked up or absorbed and is driven out gradually. The present test is believed to verify this prediction. The voltage used in the present case was 30,000 volts on a 13,000-volt insulation and was applied until temperature equilibrium was obtained in each case.

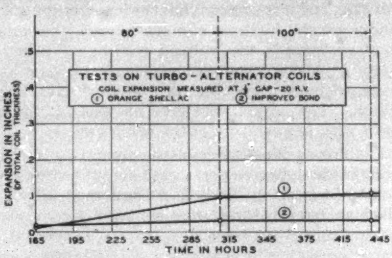

FIG. 4

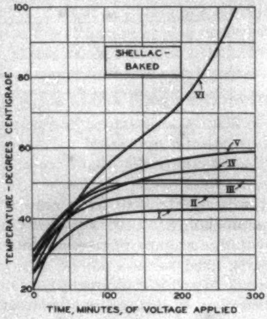

FIG. 5

Figs. 5 and 6 represent standard shellac folium and that of the new bond respectively. It will be noted in Fig. 6 that baking the coils with the improved bond, no change in loss was obtained, the variation being due to variations in room temperature but in Fig. 5 after each baking, the standard insulation showed increased losses. This was not due to voids as the coils were tightly clamped. Previous to the final curve of Fig. 5, curve *VI*, this coil was baked about 18 hr. at 115 deg. cent., the temperature-time-voltage curve going up to more than 100 deg. cent. before the test was stopped, and it was evident with the increase of losses with temperature that equilibrium has been passed and breakdown would eventually occur.

Finally the coil with the improved bond was placed in a 100 deg. cent. ambient and 30,000 volts applied until temperature equilibrium was obtained (see Fig. 7). While some curing had probably occurred, the coils were tightly clamped during the test and this effect was believed to be small.

The result of the above experiments are given to show what can be done with insulation of this type, merely by a choice of bond. The data given was obtained for coils with mixtures of the bond which were as far towards the low loss side as it was convenient to use on account of the high temperatures necessary in manufacture if bonds of lower loss are used. However, such information is important in that it indicates not only possibilities in improving insulation for the present designs of machines, but also for designs when it may be desirable to increase the stress somewhat on the insulation. So far power losses have not been considered in turbine design but we are facing the problem of increased stresses and losses in many high-voltage applications and it is not probable that we shall escape here.

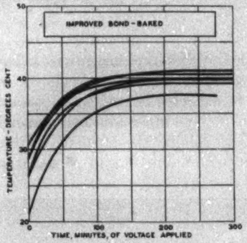

FIG. 6

One very important feature of the new bond is the flexibility of the folium as compared to shellac, and it is found possible to use several extra layers of mica which is desirable as long as the coil is good mechanically.

### BREAKDOWN TESTS

While it is not intended in this paper to suggest that higher voltage stresses be used until it becomes necessary, it is believed that enough evidence is given to indicate that the use of increased stresses may be possible and if higher and higher generated voltages become desirable as machines increase in size and output, such may become necessary. As a matter of fact there has been some increase in stresses used during the last several years. A second electrical property of insulation, that of dielectric strength, is of the utmost importance in this connection and it is doubtful if many operating engineers have an idea of the factor of safety maintained in the way of puncture voltages. Just what the factor of safety should be is a different problem but all will agree that with the large valuation involved in a single large generating unit, the factor of safety should be greater than in any other application. The problem of surges alone makes it desirable to know what the actual dielectric strength is and from this point of view, would become still more important for increased stresses. With this in mind, four coils have been tested as follows:—three coils of four ft. length designed for 22,000 volt operation using the improved insulation, were tested by using a six in. layer of tinfoil around the middle of the coil, the whole being immersed in oil. Under a continuous rise voltage test, none of the coils was punctured, all flashing over the surface at values between 150,000 and 170,000 volts. An attempt on a coil of 20 ft. in length in the straight part and three ft. extension on each end, was made in air. This also flashed over on three or four trials at about 165,000 volts. No tests were made on standard shellac folium but no great difference is to be expected on momentary tests although the improved bond will withstand the same voltage longer. It would be of interest to know what the actual puncture values are but the tests obtained were high enough to indicate a sufficiently high factor of safety even for considerably higher operating stresses than are now used. Operating stresses at present are of the order of 30 to 60 volts per mil while the puncture tests indicate values of the order of 500 volts per mil.

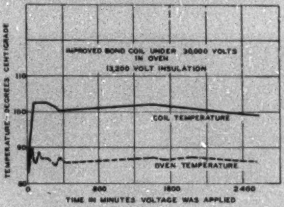

Fig. 7

## Testing Voltages

A problem which may become more or less acute upon the adoption of higher operating voltage is that of overvoltage tests. It is difficult to get quantitative data upon which to base conclusions but attention is called to the fact that the effects of voltage vary as $E^n$ where $n$ is of the order two or above and in most cases for test voltages the value of $n$ will be more nearly three. A feature of high testing voltage which has not been experienced up to the present time is that of the disruptive effects of creepage discharges on the surface of coils. Coils may be damaged to the extent of actual puncture of some of the outer layers particularly at a distance of two or three in. beyond the end of the electrode or in the machine beyond the end of the slot. Further studies will be required to determine what voltages should be chosen for tests of this type but an attempted life test on a 13,000-volt insulation using the improved bond and 40,000 volts applied between a metal clamp on the outside of a coil and the conductor, produced an effect which indicates the danger of injuring coils by the application of extremely high voltages. About three in. from the end of the electrode and extending as much as three or four in. farther, the disruptive effect of creepage charges gradually destroyed the paper and bond, loosening and dehydrating the mica so that it exhibited a bushy appearance. Breakdown finally occurred after 1140 hr. in this region while the insulation under the clamps was still in perfect condition. Further tests at 50,000 volts on the same design of coils produced the same effect and caused breakdown in a few hours. It was evident that the rate of deterioration increased rapidly between 40,000 and 50,000 volts. A test of 66,000 volts even for one minute might defeat its own purpose by damaging the surface layers of the coil unless some means of reducing these creepage effects can be devised. As shown in the following paragraphs, the corona and surface creepage effects can be reduced or removed at operating voltages and can be reduced at least, for high testing voltages.

## Corona Elimination in Turbo Stators

The phenomenon called corona made its appearance in machines as soon as voltages were developed of the order of 5000 or 6000 volts from conductor to ground. The evidence of its presence is furnished by the odor associated with ozone, which is a product of the action of corona on the oxygen of the air and it is visible to the eye under favorable conditions. While the coil is mechanically tight in the slot, there still exist some very small air-gaps due to manufacturing tolerances and irregularities of the surfaces in contact and these minute gaps are over stressed, producing corona.

So far all evidence points to the fact that the actual danger from corona is slight but there are some reasons why it should be removed if possible, as for example the coil could be held rigidly in the slot without permitting expansion as occurs when the slot liner and wrapper are eaten away. This will also eliminate the uncertainty in the minds of some designers and operators and finally may help to reduce effects of testing voltage. As much as 15 years ago engineers began to feel uneasy about its effects on insulation and the problem of its elimination was considered. It was evident that all that was necessary was to remove the voltage stress in the air-gap, which could be done by bringing ground potential to the surface of the solid insulation, by making the surface a conductor. Accordingly metallic paints and tinfoil were tried and actually put into some machines. The tinfoil was applied with an outer covering of cotton tape and was grounded at but one point, otherwise the steel laminations would be short circuited. The paints were usually too high in resistance to be efficient. Along with the difficulties of applying and the fact that corona in mica insulated machines without this kind of protection did little damage the problem was dropped as mica was generally used. However, it has seemed more and more desirable to remove the corona if such could be done without too much difficulty and with the possibility of higher generated voltages the problem will become even more important. For this reason the present study has been extended to include the problem.

Some features of a solution of the corona problem are self evident. The conducting film to be placed on the coil must be continuous and adhere to the insulation surface. Further, the resistance of the film must be large enough to prevent eddy currents and in case of grounding at more than one point, should also be high enough to prevent circulating currents. Metallic films in general fall in a class with resistances too low to be used and at best could be grounded at but one point. In case this ground was broken most of the effectiveness of the film might be lost. For this reason a film of high enough resistance to permit of more or less continuous grounding throughout the slot is the ideal. The upper value of resistance is determined by a maximum value which will permit a charging of the condenser between the conductor and film to the full potential of the machine during a half cycle. Calculations show that the resistance per unit length of coil can be as much as a megohm even for relatively few grounding points. On the other hand, a minimum of 1000 or 2000 ohm per in. length of coil is sufficient to eliminate eddy and circulating currents so that a wide range of workable resistance exists.

One special graphitic paint has been found to adopt itself rather readily to the purpose. By controlling the concentration the resistance can be made the order desired and high enough so that continuous grounding can be used if necessary. It is not improbable that a number of materials can be found which have the proper characteristics but the one mentioned seems to have most of the desirable properties in case a smooth surface is furnished for its application. A problem, concerning which there is some uncertainty as yet, is that of the life of the film at the vent ducts under the action of the high velocity air currents used in cooling the machine. To avoid the possible destruction of the film at this point, the film can be protected by retaining the fish paper slot liner, perforating this paper layer at points between each vent duct along the side of the coil and painting over the hole on both sides with the same graphitic paint so that the film also covers the edge of the paper in the perforation. This has been shown to give perfect grounding and since the paper lining of the slot is protected from the corona it should protect the film over a long period of the life of the insulation.

The conducting film (See Fig. 10) just discussed removes the corona throughout the slot but at the end of the slot corona occurs which gradually tends to eat away the film itself. Furthermore, this corona will of course tend to destroy the organic material on the surface of the coil and must be eliminated before the device is complete. Burying the end of the film deep in a solid insulation suggests itself as a means of eliminating this defect, but the space available is small between the coils and needed for ventilation purposes. Two other methods have also been suggested and one will be given which has been perfected to the point where it is believed to be practical.

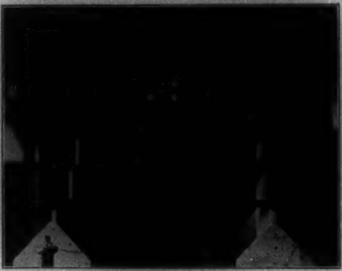

FIG. 8

If an extension of the conducting layer is made a few inches beyond the slot, a capacity current flows along this extension charging up the condenser between the layer and the conductor. The capacity, of course, is small, being of the order of 15 $\mu \mu$ f. per in. length of coil, and the currents flowing are also small, decreasing towards the end of the extension. Calculation shows however, that if resistances of the order of 100 megohms per in. length of coil could be found the $I R$ drop along this extension could be made to take care of most of the voltage difference between the conductor and ground so that at the end of the extension, the voltage is too low to ionize the air, thus removing the corona completely. Dependable materials giving the desired resistance have been found available and some idea of the effectiveness of the device is obtained from Fig. 8. *A* represents the corona between a laminated structure and coil at 30,000 volts applied with no attempt at elimination, *B* shows the effect of the graphitic layer under the same conditions with the end effect, which is later eliminated in *C*. It is possible to damp out 30,000 volts with a minimum of approximately a five in. extension; 8000 volts can be taken care of with approximately a two in. extension, leaving the drop at the end below the corona point.

The accurate solution of the problem involved in the extension is a particular solution of the transmission line equation for parallel conductors with uniformly distributed resistance and capacity, the differential equation being

$$\frac{\partial^2 E}{\partial x^2} = C R \frac{\partial E}{\partial t}$$

The inductance is considered negligible.

The solution of this equation may be found in engineering texts but for practical purposes the order of magnitude of the resistance can be obtained from the approximate equation

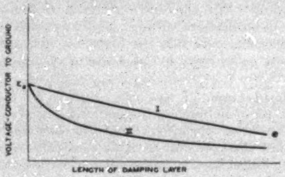

Fig. 9

$$r = \frac{2\,(E_0 - e)}{C\,\pi\,f\,l^2\,10^{-12}\,E_0}$$

Here *r* is the resistance per unit length, $E_0$ the applied voltage, *e* the residual voltage at the end of the extension, *C* the capacity per unit length, *l* the length of the extension, and *f* the frequency. For lengths, permissible in practise, the value of *r* is found to be of the order of 100 megohms per in. length of coil. The values actually used are approximately 500 megohms per in. as measured by a 1000 volt megger. The resistance of materials of the type available vary with voltage of course, and are somewhat lower under machine voltages.

A feature of the damping resistance or extension which may be of interest is represented in Fig. 9. In order to get a uniform drop in voltage per inch of extension, curve *I*, which is the ideal way, the resistance per unit length would be required to vary inversely as curve *II* of the Figure. This is impossible in practise where the resistance is constant per unit length so that the voltage drops off more nearly as curve *II*.

In building the extension it has been found necessary to use a porous material to hold the resistance material and a special asbestos tape with the organic filler burned out. It has been possible to do this without loosing much of the mechanical strength of the tape and some of this loss is regained when fastened to the coil surface with a bond. The tape is then filled with the high resistance material and electrical connection made with the graphitic layer, Fig. 10 shows the complete assembly.

## Corona in End Windings

A problem which has caused some discussion in the past has to do with the formation of corona on the metal parts of the structure bracing the end windings. So far this problem has not been of much importance for the type of bracing used with mica folium coils, as enough insulation could be used between the metal parts and the coils, that operating voltages could produce only a soft, harmless corona at most. The question may be revived, however, with voltage increases in machines, but the problem in any case can not be considered serious since types of bracing can be used in which extra insulation can be added to bring the stresses in the air-gap below the corona point. It is a simple matter to calculate the air-gap stresses on the basis of the insulation thickness and dielectric constants or in other words, to calculate the insulation thickness necessary. The metal parts in such cases are to be assumed to be at ground potential, that is, at the average of the coil potentials, thus insuring that no high voltages are built up across the insulation at any point. From this point of view it is necessary to ground all metal parts, but in general this is more important in that it permits better mechanical features.

Reference was made above to the effects on insulation of corona in hydrogen. The usual deterioration of organic material in the presence of air under corona is due chiefly to oxidation. With hydrogen this effect will be absent[3] and the bad effects usually associated with corona should disappear as long as the arc temperatures are not too high where they actually strike the insulation. Even intense corona has been found to have but slow effect under short tests of a few weeks.

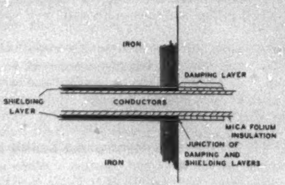

Fig. 10

For the same reason, the absence of oxygen protects laminated insulation from internal corona.

## Summary

A summary of the above discussion may be made as follows:

1. That as generated voltages are increased it may become necessary to use higher voltage stresses in volts per mil thickness of the insulation, which in turn

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[3] Knowlton, Rice, and Freiburghouse, *Hydrogen as a Cooling Medium for Electrical Machinery*, Trans. A. I. E. E., Vol. XLIV, 1925, p. 922.

may necessitate the use of a lower power factor material in order that excessive heating be avoided.

2. That a very decided improvement in this property can be obtained for mica folium by a choice of bond containing only a negligible amount of a low loss solvent or other volatile material.

3. That the reduction of the solvent decreases the tendency of such coils to expand, and it has been found that the swelling is reduced to a small fraction of that of older insulations.

4. That the factor of safety to puncture as determined by continuous rise voltage tests is considerably more than is ordinarily considered necessary for most applications and that the results indicate higher stresses on mica folium could be used.

5. That so far the effects of corona have not been serious and in no case has the mica been affected, yet to protect the organic surface of the coil, it may be desirable to eliminate corona at present voltages as well as at higher voltages. In hydrogen it will not be so important.

6. That a method of eliminating corona on armature coils has been devised which is believed to be practical.

## Discussion

**P. L. Alger:** Mr. Hill has given us a very interesting and suggestive article, which I am sure will be a valuable contribution to the literature. Mr. Hill evidently believes, and I fully agree with him, that the whole subject of insulation of armature coils hinges on two points, the first being the choice of the sticker to hold the mica together, and the second being how to avoid corona discharges.

Any sticker used must be not only a good insulator, heat resistant, and acid resistant, but it must also be so flexible that it can be applied, and the coil can be handled and taken out of the machine and put back without damage, while at the same time it must have so high a boiling point or melting point that it will not flow under operating temperatures. In cables, flowing is permitted because the insulating material is held by a sheath, but in an armature coil this is not possible. Since any material like varnish is inherently flexible, if it has a low boiling point, and brittle if it has a high boiling point, these two requirements of flexibility and high temperature resistance are incompatible, and it is very difficult to strike a balance between the two. As Mr. Hill has said, shellac is all right at low temperatures, but when heated it loses alcohol and becomes very brittle. We have found that black asphalt varnishes give the best results, partly because they contain many ingredients of slightly different boiling points, so that by aging them to any desired degree, the boiling point can be raised just enough to avoid swelling in operation, while at the same time the maximum of flexibility is secured.

In regard to the corona question, it is interesting to think at how low a voltage corona occurs in armature coils. The dielectric constant of mica insulation is about 3 in magnitude, which means that the air in series with the insulation is subjected to a stress about three times as great as that in the insulation itself. This, coupled with the fact that the external air spaces are irregular, gives actual maximum stresses at certain points in the air surrounding the coil, of five or six times that in the insulation and therefore, external corona begins at very low voltages—as a matter of fact, at about 3000 or 4000 volts on a 22,000-volt coil. It is, therefore, very difficult to avoid it completely. We have found that, by using simple asbestos tape armor on the outside of the coil, good results are obtained. Asbestos is sufficiently conducting to hold down the potential of the coil surface near the embedded parts below the sparking voltages.

Great variations in surface conductivity occur with changes in humidity, with dust, and with the type of varnish coating employed on the end windings, but in general values of surface resistivity of the order of 50 megohms per in. of perimeter per in. length of coil give good results. The accumulation of dust on the end windings of machines in service acts initially as corona protection, thus accounting for the diminution of ozone often noticed after machines have operated for some time. Too much dirt, however, lowers the surface resistivity too greatly, causing increased discharges.

Fortunately, corona can be permitted without giving much operating trouble, as shown by the fact that two 22,000-volt synchronous condensers have been operating in India for the past five years without any corona protection whatever, but with insulation consisting of mica tape and black asphalt varnishes around the entire coil. These machines have so much corona on the end windings that the lines between the terminal coils of each phase and the adjacent end windings of the next phase are continually illuminated by a line of light during operation. In spite of this, they have operated for five years without noticeable deterioration. Thus, while external corona is of great importance, especially in high-potential tests, it is not really a thing to be regarded as a source of danger to mica-insulated machines in normal operating conditions.

**S. L. Henderson:** I was very glad to have confirmation from Mr. Alger of so much of the material that was in Mr. Hill's paper. It has been very interesting to me, as a machine designer, to realize that the problems of cable manufacture are much the same as we have in our insulations. We are bothered with moisture and voids in the insulations and have the problem of porosity in the paper. We can pick a paper that is low in moisture but too brittle to use, and we are working between the same limits. We are also trying to reach the same solution of finding an insulation that will remain through its life practically as good as the day it was made.

**C. F. Hill:** I was much interested in Mr. Alger's remarks and note in particular that his experiences in general are similar to our own. One point in particular, involving the use of asbestos tape armor, is of especial interest. We have found that asbestos tape at room temperature takes up moisture until it is sufficiently conducting to make a fairly good shield over a coil surface and have found that it is especially valuable on coils at room temperatures when high-voltage testing is done as it tends to prevent static discharges over the surface which might mar the surface layers of the coil. Asbestos, however, is a rather good insulator when dry as in a hot machine and our experience has been that it then does not eliminate corona. We have also found it desirable to bake out the organic filler of asbestos tape before applying to the coil in order to insure that static discharges under high-voltage testing may not burn conducting paths through the tape. This is especially necessary, for example, in the case of 22,000-volt insulation when applying up to 70,000 and 80,000 volts.

Mr. Alger's remarks on corona in operating machines are in general agreement with our experiences. In the slot, however, corona will attack all exposed organic material and it is to preserve the surface that corona eliminators are applied and then only for higher voltage operation. As to the choice of bond used, any bond must be a compromise of properties and for extremely high-voltage operation the electrical properties must assume an important role. An attempt was made in the paper to give a complete picture of the requirements for turbo coil insulation and to give an idea of what could be done in the way of approaching, at least, a good insulation. Shellac from alcohol solution is at a disadvantage in some respects. On the other hand, shellac with the alcohol omitted entirely can be made with excellent properties, far better mechanically than asphaltic bonds, but difficult to process at present into this type of insulation. We believe that the low-loss characteristic of asphaltic bond gives it some advantage as yet for high-voltage operation.

# The Gould Street Generating Station of the Consolidated Gas, Electric Light and Power Company

BY A. S. LOIZEAUX[1]
Associate, A. I. E. E.

***Synopsis.***—*The paper is descriptive of the Gould St. Plant. Pulverized coal is prepared in a separate building. Only one boiler is provided per turbine, each boiler delivering a maximum of 520,000 pounds of steam per hour. Automatic control is provided for the electric drive of boiler auxiliaries, electric auxiliaries being used throughout the plant. 250 volt exciter and 460 volt house turbine are on main generator shaft. Switch house is of isolated phase construction with vertical operation of switches. Actual costs are given for the first unit, with estimated costs for completed plant, resulting in costs for the completed plant of $88 per kw. for normal output and $80 per kw. for maximum output.*

* * * * *

THE new Gould Street Plant which began operation in January, 1927, is located in the City of Baltimore on the Patapsco River, an arm of the Chesapeake Bay. This waterfront site was formerly the power plant location of the Baltimore Electric Company which had been purchased by the Consolidated Company in 1908, and has not been in operation since 1918. The comparison between the old plant and the new illustrates the great advance in the art of electric power generation during a period of 20 years, the new units having twelve times the capacity of the old, with a coal rate of the new plant less than one-half that of the old plant.

From the standpoint of nearness to important load centers the site is highly desirable so that the energy is distributed by underground cable at 13,200 volts without transformation. The plot measures 405 ft. by 635 ft. and is of sufficient size to supply load growth for perhaps 10 years, when the progress of the art of power generation will probably make it desirable to begin anew in another location with higher pressures, higher temperatures, and, perhaps, a materially different heat cycle.

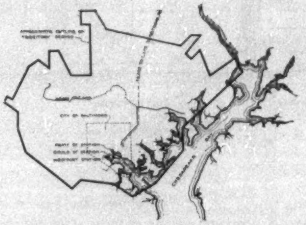

FIG. 1--TERRITORY SERVED BY THE CONSOLIDATED GAS, ELECTRIC LIGHT & POWER CO. SYSTEM

### SOURCES OF POWER IN BALTIMORE

The accompanying map, Fig. 1, shows the territory served by the Baltimore plants and indicates the city limits and the location of the Westport and Gould St. plants; also the former railways plant at Pratt St.

The Westport plant began operation in 1905 and provided for growth of load through 1926, a period of 21 years. Westport has a 25-cycle capacity of 125,000 kw. and 60-cycle capacity of 40,000 kw.

The Pratt St. plant was formerly a railway generating station but now contains only one standby unit of 20,000-kw. capacity.

### HYDRO ENERGY

A considerable part of the electric energy used in Baltimore comes from the Holtwood plant of the Pennsylvania Water and Power Co. The Holtwood plant is located on the Susquehanna River at Holtwood, Pennsylvania, and consists of a hydroelectric plant with 87,000 kw. in 25-cycle capacity and 24,000 kw. in 60-cycle capacity. There is also a steam station at Holtwood of 25,000-kw., 60-cycle capacity. The transmission lines from Holtwood to Baltimore are 25-cycle, 66,000-volt, 40 mi. long.

### GOULD STREET GENERATING CAPACITY

Gould St. has one 36,000-kw. unit operating and a second duplicate unit which will begin operation in April, 1928. The plant is designed for four 36,000-kw. units, a total of 144,000 kw. at 60 cycles.

### ARRANGEMENT OF PLANT

The general view in Fig. 2 shows the arrangement of the plant, the power house being built on the water's edge. The coal unloading tower is placed about the center of the bulkhead line. Coal is transported by belts to the pulverizing plant. The buildings of the former generating plant were used, the old boiler house being transformed into a pulverizing plant and the old turbine room into a service building and machine shop. The switch house is a new building on the north end of the property toward the city, the power station and switch house being connected by underground concrete tunnels.

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[1] Electrical Engineer, Consolidated Gas, Electric Light & Power Co., Baltimore, Md.

*Presented at the Regional Meeting of the A. I. E. E., District No. 2, Baltimore, Md., April 17-19, 1928.*

## FOUNDATIONS

The waterfront end of the site was reclaimed from the river by filling in. The land adjacent to the power plant is to be a city pier, providing a ship channel 35 ft. in depth. These conditions made it necessary to use reinforced concrete caissons to support the end of the plant abutting on the water. Fig. 3 shows a plan of foundations. The caissons are eight in number, some circular and some oval, and are sunk to a depth of 40 ft. to a bottom of gravel and stiff clay. This construction insures that the 35-ft. deep channel will never threaten the stability of the power house.

Fig. 2—Aerial View of Generating Station

The coal unloading tower rests on two oblong caissons sunk to a depth of 70 ft. The forms for these caissons were built of timber and steel and launched like boats and sunk into place, the open method of sinking used to 50 ft., and the compressed air method, from 50 ft. to completion. A third caisson is provided to support an additional or twin coaling tower that will be required for the completed plant.

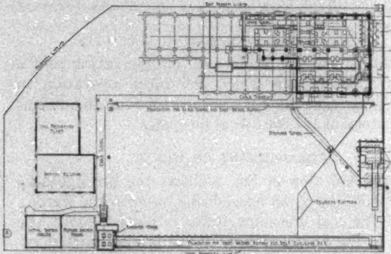

Fig. 3—Foundation Plan for Buildings, Coal Handling Equipment, and Coal Storage

The waterfront end of the coal field rests on a relieving platform in order to prevent the weight of coal from moving the soft underlying material. This relieving platform rests on wooden piles driven on 3-ft. 8-in. centers and consists of a reinforced concrete slab 18-in. thick and good for a load of 2630 lb. per sq. ft., making it safe to store coal 40 ft. deep over the area.

Other foundations for buildings, runways for coaling bridge, and foundations for turbines are all supported by wooden piling, capped with reinforced concrete mats. The mat for the turbine foundation is 3 ft. thick and is isolated from other building foundations.

## COAL SUPPLY

The coal used in Baltimore power houses comes from upper West Virginia and central Pennsylvania coal fields, over three railroad systems. A differential of 25 cents per gross ton exists in favor of water delivery of coal as compared with rail delivery. The result of this differential is that in all of the three plants coal is received by water delivery.

The company maintains its own fleet of two steam tugs and nine coal scows to transport coal from the unloading piers of the railroads to the waterfront unloading equipment at the several stations.

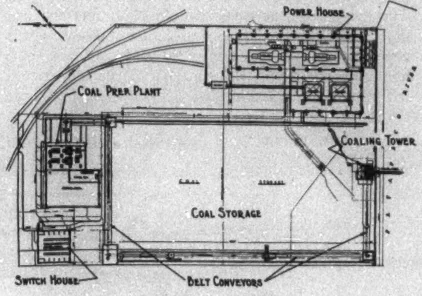

Fig. 4—General Plan of Station showing Power House, Switch House, Coal Preparation Plant, Coal Handling Equipment, and Storage Lot

During the year 1927, the Baltimore plants consumed 301,666 short tons of coal, the average analysis being 14,090 B. t. u. and an ash content average of 8.27 per cent.

## COAL HANDLING

At the Westport Plant, there are two unloading towers, both electrically operated, and an aerial cable for stocking out and reclaiming coal, the maximum stock of coal on the lot at one time being 76,025 tons.

At Gould St. the coal field is designed for a traveling bridge and the lot will hold 70,000 tons when stored to a depth of 40 ft. Fig. 4 is a general plan of the station and shows the coal handling equipment and coal storage lot.

Coal is unloaded by an electrically-operated tower with Mead Morrison equipment and a two-ton bucket, the present tower having an all-day capacity of 165 tons per hour. The future Twin tower will increase the capacity to 300 tons per hour. The coal, after being unloaded in the tower hopper, is received by a Bradford breaker 12 ft. by 19 ft. This breaker reduces the coal to a maximum size of 1¼ in. and removes trash, delivering such material through a chute to an outside location.

### BELT CONVEYERS

The belt conveyer system consists of five belts with two trippers. The first conveyer receives coal from the hopper under the breaker in the coaling tower and travels parallel to the bulkhead to the southwest corner of the lot, where it delivers coal to conveyer No. 2. This belt carries the coal along the western side of the field and either stocks the coal out in the field by means of a tripper, or delivers it to a secondary crusher.

The secondary crusher is installed in a concrete pit at the junction of No. 2 and No. 3 belts and receives coal by gravity from conveyer No. 2. This crusher is a hammer mill of steel plate construction built by the Pennsylvania Crusher Co. It is rated at 200 tons per hour but can handle 400 tons of dry friable coal.

No. 3 conveyer carries the coal along the northern edge of the field. It is inclined at an angle of 19 deg., and lifts the coal 77 ft. from the pit under the hammer mill to the No. 4 conveyer, which carries the coal into the end of the preparation plant above the bunkers. No. 4 conveyer is also inclined 19 deg. and lifts the coal 24 ft.

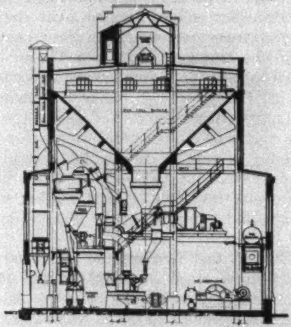

FIG. 5—CROSS-SECTION OF COAL PREPARATION PLANT

No. 5 conveyer distributes the coal in the raw coal bunkers by means of a traveling tripper.

All of the conveyers are equipped with 36 in. rubber belts and have a capacity of 336 tons per hour. There is no speed adjustment on any of the belts; the ribbon principle is used, the rate of feed or thickness of ribbon of coal is regulated by the apron feeder which delivers coal to the Bradford breaker. The flow is continuous from this point until the coal is delivered to the preparation plant bunkers. A similar regulation is provided at the traveling hopper above No. 2 conveyer when coal is reclaimed from storage. Electrical interlocks are provided so that in the event of trouble on any belt all preceding equipment including apron feeder and breaker will be immediately stopped preventing an accumulation of coal at the junction points.

The belts are arranged so that any one of three operations may take place; *viz.*, tower to preparation plant bunkers, tower to storage, or storage to bunkers. The motors for these conveyer belts, five in number, are controlled by push buttons which operate single-step primary resistance starters, the resistance being cut out by the operation of a small motor driven definite time relay.

### STORAGE AND RECLAIMING EQUIPMENT

At the present time coal is being stocked out and reclaimed by a gasoline engine driven, crawler crane, equipped with a one-yard grab bucket. The capacity of this rig is about 60 tons per hour.

When the third generating unit is installed, it will be necessary to purchase the traveling bridge. The runways for the bridge are in place, since the concrete work was so intimately connected with the supports for No. 2 conveyer on the west side and the cable tunnels on the east side, it was economical to pour them while the concrete plant was set up.

### COAL WEIGHING AND SAMPLING

Two Merrick weightometers are used to weigh the coal in transit. One is installed on No. 1 conveyer and weighs all coal received at the plant. A second is located on No. 4 conveyer and gives a record of the coal sent to the preparation plant bunkers.

A Dings magnetic pulley is used at the head of No. 4 conveyer. It serves to prevent any magnetic material from getting into the bunkers above the pulverizing mills. This gives triple protection since the Bradford breaker removes the larger pieces of foreign material from the coal, the hammer mill is equipped with tramp iron pockets which catch a part of the foreign material and the magnetic pulley throws out the nails, small bolts, etc., that remain.

An automatic coal sampling device is now being installed at the junction of conveyers No. 1 and No. 2. It consists of a rocker shaft carrying several 4-in. tubes for collecting the gross sample, and a Sturtevant motor driven sample crusher and splitter. It is arranged to run whenever No. 1 conveyer is in operation, and does not require a separate control. The gross sample taken by the tubes will average one pound per ton and will be taken simultaneously at several points in the ribbon of coal as it leaves the head pulley of the conveyer. This gross sample will be crushed and split so that a sample of about two pounds per hundred tons will be collected for the laboratory while the discard will run by gravity onto No. 2 belt and pass on with the other coal.

### COAL PREPARATION PLANT

The general arrangement of the coal preparation plant is shown in Fig. 5. The building was originally the boiler house of the former plant. All but two of the original boilers were removed, the two remaining boilers being used to supply steam during the construction period. The building required considerable alteration including the removal of the old coal bunkers and the installation of new bunkers with increased slope so that the coal would flow to the discharge gates at the bottom of the bunkers, the capacity of the bunkers being approximately 900 tons. The coal gates at the bottom of the bunkers control the flow of coal to Richardson automatic scales now being installed. There are two scales for each mill. From the discharge hopper of the Richardson scales the coal flows to two feeders for each mill. The original installation included steam driers but these have been replaced by the system of drying in the mill. Air from a tubular air heater using steam at boiler pressure is blown into the circulating air as it enters the mill providing hot dry air to absorb moisture from the coal in the mill. Sufficient air is bled off from the top of the cyclone to discharge the moisture picked up and keep the humidity of the air in the circulating system below the dew point. This air bled off is replaced by heated air coming from the air heater which is mixed with the re-circulating air before it enters the mill. The cyclones in which the air and coal are separated discharge the coal into the hoppers above the coal transport pumps. The air drawn off from the circulating system passes through a concentrator, in which the heavier solids are removed, and from there it passes through a washer before being vented to the atmosphere. This washer is of the vertical type, in which the gases are washed by steam and water sprays.

The machinery for preparing and transporting the coal comprises two 20-ton Raymond roller mills, each with a separate exhauster and circulating system and steam air heater; two transport pumps, each having a nominal rate of capacity of 40 tons per hour, and two 735-cu. ft. two-stage motor driven air compressors.

The construction within the mill house is such that wherever possible, ledges, or resting places for coal dust have been avoided. As two of the old boilers were left in service for furnishing construction steam, a cinder block wall was built to separate the grinding room from that section of the old building where the boilers remain. Sash in the preparation plant opens outward and is of the plain glass type, providing a 10 per cent area of plain glass, as prescribed by the underwriters.

All of the equipment in the preparation plant is electrically driven, using 440-volt, three-phase, 60-cycle, squirrel-cage type motors. There are no circuit interrupting devices in the preparation plant. Motors are controlled from water-tight push buttons operating contactors which are located in a control room, which is located in the turbine room of the old plant. Sequence interlocks are provided on the controls to prevent stopping equipment in incorrect order and consequent flooding or jamming of the coal feeding system. Small motors are thrown directly across the line, but the motors for the mills, mill exhausters, dryer exhauster, transport pumps, and air compressors are started by primary resistance type contactor control. Resistance grids are in the control room. Lead covered wire and cable are used for the power circuits. Control buttons are mounted adjacent to each piece of apparatus and also on a control board. The operator in charge of the grinding also controls from this board the switching valves in the coal lines over the bunkers in the boiler house.

### COAL TRANSPORT LINES AND COAL BUNKERS

Coal is pulverized in the mills so that 70 per cent will pass through a 200 mesh screen. After collection in the cyclones, pulverized coal enters the transport pumps and in combination with compressed air is transported through 6 in. pipe lines about 750 ft. long to the bunkers in the power house. The transport pumps and pipe lines are in duplicate and are so arranged that either pump can handle the output of either or both mills. The two boiler bunkers may be fed by either of the transport lines, selection being obtained by electrically operated transport valves located over the bunkers and controlled from the preparation plant master panel. Paralleling the transport lines is a 1½-in. line with connections to each for purging them with compressed air. The coal level in the bunkers is indicated on individual boiler control panels and also on the preparation plant master panel. A specially developed device takes periodic "soundings" in the bunkers and operates Selsyn transmitters for this service. Two high level paddles are also installed in each bunker to give a flashing lamp indication when the bunkers are nearly full.

The powdered fuel bunkers are each 100 ton, V-shaped, structural steel, insulated on the outside to prevent condensation inside the bunker. All parts of the bunkers are welded and tested water-tight.

### CROSS-SECTION OF POWER HOUSE

Fig. 6 is a cross-section of the power house showing a rather compact arrangement of equipment, yet providing ample space for operation. Abundant natural light and ventilation is provided for both turbine room and boiler room. A pipe gallery provides for longitudinal runs of pipes. The electrical gallery is open to the turbine room and on the same level as the turbine floor giving easy access to electrical operation.

### COAL FEEDERS

The coal is fed by four quadruplex screw feeders per boiler to sixteen Lopulco type burners through 6-in. pipes crisscrossed to prevent stratification in the furnace in the event of outage of one or more feeder groups.

### FURNACE

Three sides of the furnace are water-cooled by fin-tube surface backed by special tile, rock wool insulation and steel casing. The front wall is of firebrick, cooled by the preheated secondary air, admitted to the furnace through ports at sixteen levels in this wall. A water screen interconnected with the rear wall circulating system protects the inclined floor of the furnace which forms the ash hopper.

### AIR SUPPLY AND GAS REMOVAL

Primary air, used to convey powdered fuel from the screw feeders to the burners, is a mixture of preheated air tapped from the secondary duct and tempered with room air. Primary air is supplied by two fans per boiler, connected on the discharge by an air bus, which makes any fan available for either boiler. Two forced draft fans per boiler furnish the secondary air taken from the room and discharged into a plenum chamber directly ahead of a C-type plate preheater mounted above the gas outlet of the boiler.

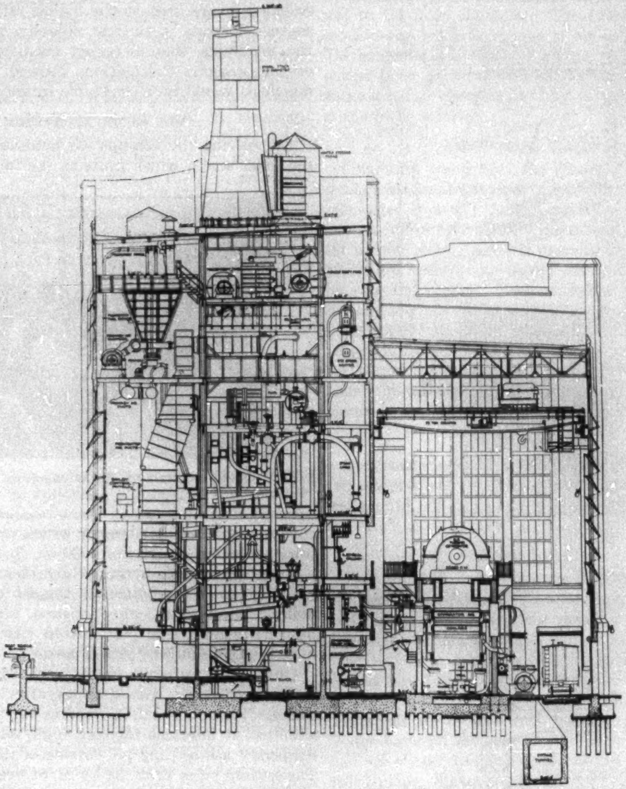

FIG. 6—CROSS-SECTION OF TURBINE ROOM AND BOILER HOUSE

Tertiary air is taken from the secondary air duct for admission around the burners.

The gases leaving the preheater are removed by two induced draft fans and discharged into an eleven-ft. diameter self-supporting unlined steel stack, one per boiler, extending 213 ft. above the burner arch.

### BOILER

The use of one boiler for a 36,000-kw. turbine with only one additional boiler as a spare unit marks an advance in plant design. Each steam generating unit has a maximum output of 520,000 lb. per hour at 450 lb. drum pressure and 725 deg. fahr. superheater outlet temperature, which is sufficient for about 46,000 kw. turbine capacity. Reserve capacity gained by increased size of boiler auxiliaries even at some sacrifice in normal operating economy, was found to be more economical than the addition of spare boiler units. Four turbines will ultimately be supplied by five boilers. Fig. 7 is a section of boiler and furnace.

Several features in the design of the boiler, a conventional B & W cross drum steel encased type, were unique. It was the first boiler at 450 lb. pressure to have 4-in. tubes. A considerable increase in heating surface was gained at small expense by extension of tube length from 22 ft. to 24 ft. Modifications in the manufacturer's previous design allowed an advance from 385 pounds to 450 pounds operating pressure. The drum diameter, 60-in., was the largest attempted for that pressure at that time, and the length of 34 ft. was the greatest that the manufacturer could furnish without a girth seam. Two steam outlets were insisted upon. General Electric steam flow meters modified for use as water level indicators and recorders are installed at the operating floor level.

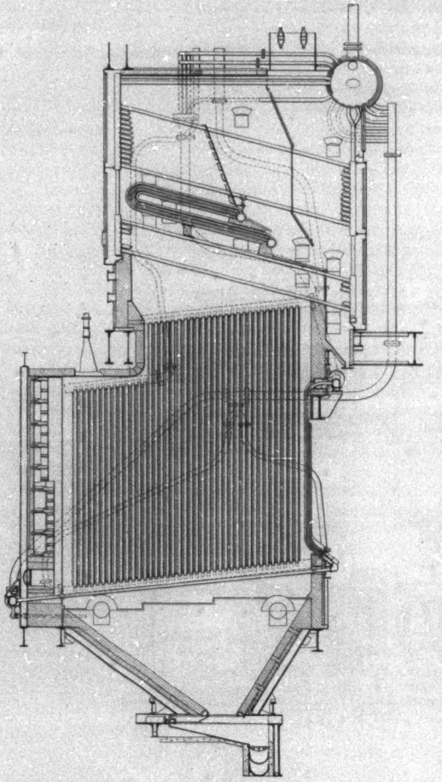

Fig. 7—Cross-Section of Boiler and Furnace

### Superheater

The superheater is of three-pass hair pin loop construction of the interdeck type and is located between the 5th and 6th rows of boiler tubes. To avoid excessive pressure drop at the higher ratings and a consequent decrease in turbine capacity, the diameter of the manifolds was increased considerably over the original design. Calculations showed that the larger manifolds would be a profitable investment.

### Ash Removal System

Ash leaving the combustion chamber falls through the water screen which protects the furnace floor, and collects in the ash pit hopper which is lined with fire brick and has a capacity of 4000 cu. ft.

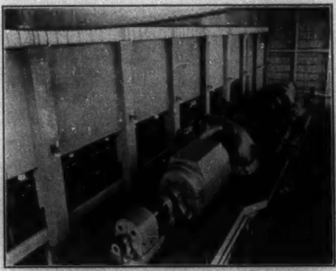

Fig. 8—View of Turbine Room showing No. 1 and No. 2 Units

Three horizontal, hydraulically operated ash gates are provided on the bottom of the ash hopper for each boiler. Those gates, when opened, allow the ash to drop on inclined feed plates from which it is washed into the main sluice by jets of water.

Large clinkers are retained on a grizzly over the sluice and are broken up with a sledge after the ash gate is closed. The ash is transported in the sluice by water admitted at intervals through high velocity jets to a temporary ash settling pit outside of the boiler house. The settling pit is 12 by 28 by 21 ft. deep with sides of steel sheet piling and is provided with adjustable baffles to assist in settling the fine ash. An overflow is provided for the water which discharges to the sewer. The ash is removed by a clamshell bucket on a crawler crane, loaded into trucks, and hauled to the ash dump.

### Turbo Generator

Fig. 8 gives a view of No. 1 unit in the foreground, and unit No. 2, under construction, in the background. The alternator is a 43,750 kv-a., 80 per cent power factor, 1876 rev. per min., 13,200 volts., three-phase, 62½ cycle machine, which is designed to operate later at 60 cycles. In addition to the main generator there is a shunt-wound shaft exciter rated at 250 kw., 250 volts d-c. overhung on the main shaft and beyond this and connected by means of a Fast flexible coupling is an auxiliary generator having a capacity of 1500 kv-a. at 80 per cent power factor and 460 volts, three-phase, 62½ cycle. The overall length of the turbo generator unit is 69 ft.

The turbine is a 13-stage Rateau impulse machine of 36,000 kw. capacity and drives the main generator through a Fast flexible coupling. It is a modified form of a turbine of lower normal rating of the non-bleeding type. The initial stages, however, have been opened up to pass the additional steam used in bleeding. Steam is supplied at a normal pressure of 390 lb. and a total temperature of 700 deg. fahr. Steam is bled at the 3rd, 5th, 8th, and 10th stages at full load pressures of 193, 99, 30, and 9 lb. absolute respectively. The turbine is designed for highest efficiency at 25,000 kw. load; and when bleeding steam at four points the unit can produce a net station send-out of 36,000 kw., which is the company rating of the machine. A considerably larger output can be produced by bleeding at the two lower points only.

### Generator Cooling

Both the main and auxiliary generators have closed re-circulating air cooling systems with two banks of coolers in each, one bank using condensate and one harbor water. The harbor water coolers are connected in parallel with the condenser circulating water system but have a roof tank connection for emergency. Condensate cooling is sufficient except for the summer months. The harbor water bank alone will provide sufficient cooling for maximum requirements.

Oil coolers are provided in duplicate, one using condensate and one harbor water, and arranged for individual or series oil circulation.

### Condenser

A 30,000-sq. ft., two-pass condenser is bolted directly to the bottom of the turbine exhaust casing and is supported partly by the casing and partly by springs on structural piers on the basement floor. The circulating water passages are so arranged that the cooler water leaving the air devaporizing and cooling section is returned in the second pass in the annular ring of tubes around the outside of the top section with which the exhaust steam first comes in contact. The shell is eccentric with the tube sheet, providing a steam belt which on one side extends to the hot well, which prevents excessive condensate depression.

The tubes are rolled into both tube sheets, a new feature of design that is discussed in other papers.

### Air Removal

Air is removed from a devaporizing section at the bottom of the condenser opposite the steam belt through two 10-in. openings which are joined in a 12-in. manifold leading to an 8-in. manifold on a three-element two-stage steam jet air pump located on the turbine platform. This pump is provided with a two-pass inter-condenser, containing 314 sq. ft. of surface and cooled by condensate only. Vent steam from the two top stage bleeder heaters and from the vent condenser of the deaerating heater is also condensed in the inter-condenser, the drips from which drain through a 12 ft. seal to the main condenser. The exhaust from the second stage jets is condensed in the after condenser. The combined capacity of the three elements on the pumps is 59 cu. ft. of free air per minute at 29 in. vacuum. Two elements at 17 cu. ft. per minute each are normally sufficient.

### Circulating Water

Circulating water from the Patapsco River passes through bar iron trash racks at the water front, under a submerged arch and through traveling water screens into an intake tunnel which will extend the length of the turbine room. Space is provided for four screens which are located outside and arranged for removal by a floating derrick. Each condenser is supplied by two motor driven pumps of 20,000 gal. per min. capacity each, both of which are required under full-load conditions in the summer. The tail pipe discharges in a tunnel common to all units, which is carried westward under the coal field to the water front. A steam jet ejector is used for priming the circulating water pumps.

### Hot Well Pumps

Condensate is removed from a 1000-gal. hot well by two motor-driven two-stage opposed impeller type hot well pumps, either of which is of sufficient capacity for full rated load operation.

### Bleeder Heaters

The 3rd, 5th, and 10th stage bleeder heaters, the evaporator condenser, and the after condenser are of the vertical closed type with four passes each. The construction of these heaters is shown in Fig. 9. The tube surface is made up of ¾ in. outside diameter, No. 14 gage Admiralty tubing, which is bent into hairpin loops with both ends rolled into a single tube sheet. The shells are of steel with hammer welded joints. Water boxes on the high pressure heaters for the first unit are of cast steel, but on the second unit will be of rolled plate. Steam is introduced in each case below the tubes and the baffles are arranged so that a vapor cooling chamber is provided to which the air vent connection is made at the side of the shell.

The 8th stage heater is of direct-contact deaerating type in which part of the bled steam is used in a section into which the condensate is sprayed through jets and part is used in another section similar to the open type feed heater in which trays are located and from which the air is removed. The pressure in the heater varies as the bled steam pressure varies. This heater is in the boiler house at an elevation of 80 ft. above the boiler feed pumps, which take their water from it. With a shell capacity of 6400 gal. it serves as a closed surge tank. The only condensate in the cycle which comes in contact with air is the condensed drip in the after condenser, which passes through the deaerating heater on its way back to the boiler.

### Evaporator

Make-up is supplied by a low heat level interstage evaporator of the vertical single-effect recirculating film type using city water as feed at a maximum rate of 10,000 lb. per hour corresponding to approximately 2½ per cent of the total full-load turbine steam flow. Fifth stage steam is used and the vapor is condensed in the evaporator condenser. The capacity may be increased by a by-pass connection of the vapor line to the 8th stage heater. The evaporator is located adjacent to the closed type bleeder heaters, under the turbine platform. Removable plates in this platform allow the handling of the shell and tube bundle of the evaporator as well as of the three heaters and two condensers with the turbine room crane.

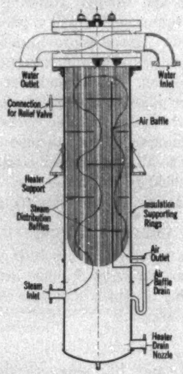

Fig. 9—Bleeder Heater of Hair-Pin Loop Construction

### Pumps and Water Storage

One five-stage motor driven boiler feed pump of 1000 gal. per min. capacity is provided for each main unit with one spare unit of the same size for each group of two units so arranged as to be available for either. A steam turbine-driven four-stage pump serving as a boiler protector only is installed with its suction connected to evaporated water and city water storage only and its discharge connected to the boiler feed mains.

Harbor water for miscellaneous cooling purposes is elevated from the screen well by two 800 gal. per min. motor-driven pumps in duplicate. A 15,000-gal. roof tank floats on the line. Two 1200 gal. per min. pumps furnish water from the same source at 125 lb. pressure for screen washing and ash sluicing. All of these pumps have bronze casings.

Condensate for make-up storage is removed from the cycle as it leaves the generator air coolers. A float in the 8th stage heater surge tank controls the amount removed. A tank of 21,000 gal. capacity at an elevation of 30 ft. above the turbine room floor receives this make-up, and further storage in two 15,000 gal. tanks is provided on the boiler house roof. Two 800 gal. pumps, arranged for either city water or evaporated water are used in this service.

City water is brought to the plant by lines from two sources. A float valve controls the supply to a 15,000-gal. tank on elevation 35, from which it is pumped to a 15,000-gal. tank on the roof.

### Piping

The single row of boilers parallel to the row of turbines makes for a very simple steam piping system. Steam is conveyed from single outlets on the Nos. 1 and 2 boilers to a four-neck manifold, from which is taken the No. 1 turbine lead and a tie to a second manifold. The second manifold is a duplicate of the first, with a connection from the No. 3 boiler and the No. 2 turbine in addition to a tie to a third future manifold. These manifolds are of seamless steel, forge welded, 25-in. outside diameter pipe. Boiler and turbine leads are 16 in. outside diameter seamless tubing designed for steam velocities of 9000 ft. per min. at rated load. Sargol joints, 600-lb. standard, with serrated faces are used throughout but valve flanges are made up with gaskets and not welded. An emergency closing valve was used on the No. 1 turbine lead but it will be omitted on the second unit. Motor-operated stop valves are used with additional remote control stations on the turbine platform.

One main and one auxiliary header is used on the boiler feed system with one feed line to each boiler from each header. All feed lines are of seamless steel extra heavy iron pipe size. Line joints and tee connections are all acetylene welded and fittings are employed only where welds cannot be used.

Lines conveying harbor water are of cast iron below the turbine room floor level, of extra heavy genuine wrought iron above the floor in sizes 2½ in. and larger and of standard pipe size brass in smaller sizes. Circulating water lines are of cast iron, atmospheric exhaust relief of fabricated steel plate welded inside and out at the joints, and all lines carrying condensate and city water are of standard steel. Welded joints have been used throughout wherever possible. The extensive use of welding has made it possible to group in a gallery space 11 ft. 6 in. wide by 11 ft. 4 in. high, with an unusual degree of accessibility, some 16 headers which will extend the length of the plant, only two of which are of sizes less than 6 in. diameter.

Eighty-five per cent magnesia insulation with a cement finish covered by 8-oz. Army duck is employed throughout. It is protected on high temperature lines by a layer of asbestos composition. Heater shells have a hard cement finish. Water boxes, turbine casing flange, and evaporator shell flange have removable blankets of asbestos fiber and cloth.

### CABLE TUNNEL

The generating voltage is 13,700 at the bus and about 13,300 at city sub-stations, the nominal voltage at the point of usage being 13,200. From the power house the energy is carried through the cable tunnel, shown in Fig. 10, to the isolated phase switch house by means of three 1,000,000-cir. mil lead sheathed cables per phase.

FIG. 10—VIEW OF CABLE TUNNEL LOOKING SOUTH

Insulation used on these cables is the standard for sub-station work—being 4/32-in. thick 30 per cent Hevea rubber and 10/32-in. Varnished Cambric. In order to prevent heating due to heavy currents in the lead sheaths, special phase arrangements were followed in pulling the cables into the ducts and the sheaths were grounded only in the centers, thus materially reducing the circulating currents.

### SWITCH HOUSE

The switch house shown in section in Fig. 11 has a basement and six floors. The side aisles of the basement are used for the high-tension potheads, this being the first and only place the phases come together. The center of the basement has been reserved for a 4000-volt distribution substation in the future. The first main floor has *C* phase equipment, the second carries *B* phase, and the third *A* phase. The operating mechanisms for the oil switches, bus disconnects, and pothead disconnects are located on the fourth floor together with the connections to the specially calibrated instrument transformers used on the water rate test circuits.

The fifth and sixth floors will extend over only a portion of the ultimate building and are used to house the control conduit boxes, station emergency lighting storage battery, and the operating room.

### CONTROL BOARD

The main control board in the operating room is a double board, semi-circular in shape. The center panels on the inner board carry the indicating meters and controls of the generators, while the end panels on either side control the outgoing feeders. The outside semi-circle carries the integrating watthour meters, relays, test switches, etc., for these various circuits.

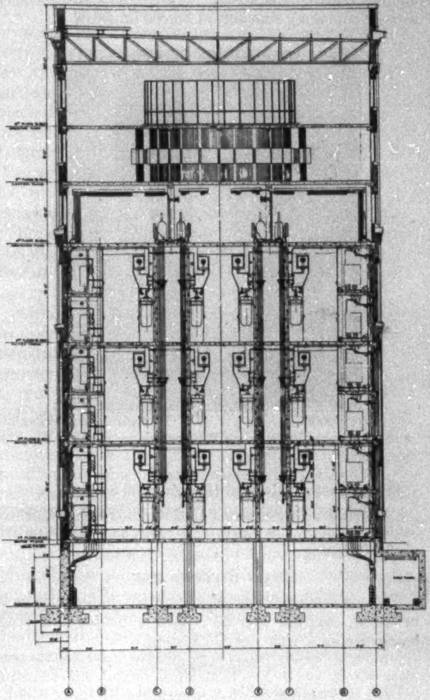

FIG. 11—CROSS-SECTION OF SWITCH HOUSE

There is another small board on the opposite side of the room which is used for the d-c. control circuits and the storage battery switching and charging.

### OIL SWITCHES

The oil switches on the outer ring bus have a rupturing capacity of 40,000 amperes, r. m. s. at 15,000 volts, based on the standard A. I. E. E. duty cycle, and they are built to operate on 15,000 volts, although standard 25,000 volt insulation is provided throughout. All generator and test bus tie circuits are equipped with 2000-ampere apparatus, while the outgoing feeders have 600-ampere oil switches and disconnects. Provision is made for the future installation of 4000 ampere bus sectionalizing switches.

The inner ring bus is equipped with switches having a rupturing capacity of 40,000 amperes on the generator and test bus tie circuits only. The feeder switches have a rated rupturing capacity of 30,000 amperes.

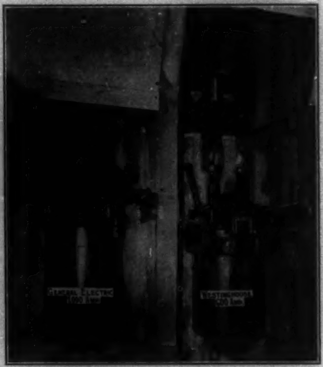

Fig. 12—2000-Ampere General Electric (Left) Generator Switch and 600-Ampere Westinghouse (Right) Feeder Switch

Fig. 12 shows a General Electric 2000 ampere generator switch on the left and a Westinghouse 600 ampere feeder switch on the right, both single pole for isolated phase mounting.

### Main Connections

The main connections of the switch house are seen in wiring diagram Fig. 13, which indicates two ring buses, giving a very flexible system.

### Reactors

Each three-phase feeder is equipped with three single-phase reactor coils, one on each phase floor, these coils having an impedance of ¾ ohm which limits a dead short circuit or ground to a maximum of 10,000 amperes, which is only one-third or in some cases one-fourth of the rated rupturing capacity of the switch. This same plan of limiting short circuits on feeders is employed in other generating stations and in substations and has resulted in greatly reducing interruptions and in maintaining bus voltage practically undisturbed by cable short circuits.

### Metering and Relays

On account of the strict isolated-phase system used it is necessary to connect all current and potential transformer circuits *YY*, thus necessitating 176-volt potential coils in some of the instruments. All neutrals of the current and potential circuits as well as those of the main generators are solidly grounded, while those of the auxiliary generators are left ungrounded.

A multi-element integrating watthour meter actuating a printometer totalizes the plant generation and gives regular demand readings hourly.

The outgoing feeders go to the city substations in groups of three, each group having selective differential relay protection by means of current balance in addition to the usual overload features. The machine oil switches are relayed to open only in case of a breakdown in the machine itself or in the leads to the switch house, differential protection being obtained with current transformers added to the neutrals. Overload on the machine circuit causes the field breakers to open and reclose, thus temporarily dropping load without cutting the generator off the bus.

### Excitation

Each machine has its own exciter bus which supplies excitation to the fields of both the main and auxiliary generators. Power is usually fed into this bus from the shaft exciter, but an emergency supply is available from a 200-kw. motor generator set.

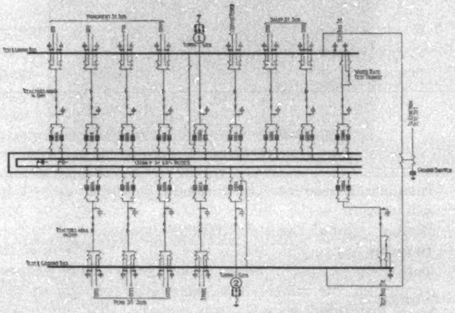

Fig. 13—One Line Wiring Diagram of Switch House, No. 1 and 2 Units

### 250-Volt Control

Throughout the plant is used 250-volt d-c. control. This voltage was adopted to conform with present day design. It effects a material saving in copper, compared to 125 volts due to the large currents necessary to handle present day equipment, and the long runs between the various parts of the plant. It also allows the d-c. generators to be rated as spare exciters, when they are of sufficient capacity.

### Lighting

Lighting in the main plant is a three-phase star system with grounded neutral. All circuits are run three-wire 120-208 volts through the panel boards with the neutral solid. In this way the failure of a single-phase transformer would only extinguish one-half of the lights on each circuit. The emergency circuits are automatically transferred from two-phase, three-wire, to d-c. three-wire when the voltage falls to 85. Return from the emergency d-c. supply to the normal transformer feed must be made by push button on the transfer contactor panel.

### 460-Volt Auxiliaries

Station auxiliaries are designed for 460 volts rather than 2300, because the lower voltage motors were lower in cost and kept in manufacturers' stocks. It was felt that the lower voltage was also somewhat safer and could be handled well by carbon circuit breakers. Carbon circuit breakers occupy less space than oil switches that would be required for 2300 volts. Their cost was lower and they are subject to inspection during operation as they are mounted on the front of the auxiliary switch board. The fire hazard with oil switches is also avoided.

### Automatic Combustion Control

The supply of fuel and air to the boilers and the removal of gas is controlled by Bailey automatic equipment which governs the speed of the forced-draft fans, induced-draft fans, and coal feeders. There is a separate control panel for each boiler. From this panel, the boiler operator controls auxiliary equipment and with the aid of signal lights and meters can tell at any time the operating condition as regards pressures, steam flow and electric power requirements for the various boiler auxiliaries. The electric circuits controlling the fans, feeders, etc., have been interlocked to shut down the equipment automatically in the event of failure of any part of the apparatus which might result in explosive mixtures in the furnace.

The induced and forced draft fan controls are the most unique in the plant. Due to the large size of the boilers and the high guaranteed rating of 550 per cent nominal rating, each of the boilers requires 1500 hp. for the four fans when operating at maximum rating. This is divided up as follows: two 200-hp. forced draft fans which introduce fresh air to the combustion chamber, and two 550-hp. induced draft fans which blow the hot gases up the stack.

The automatic combustion control used requires that the fans be able to follow very closely a predetermined speed curve of great range. To do this with a-c. motors a double speed primary is used, arranged for series connection for the first half of the range and for parallel connection the second half; large drums being used to regulate the secondary resistance for intermediate speeds.

The control for each fan consists of a low-speed secondary regulating resistance drum, a transfer switch for changing the number of poles by altering primary connections, a high-speed secondary regulating resistance drum, a balanced high-speed drum for the last five-speed points, a torque switch for starting, and the necessary circuit breakers and relays for interlocking and automatic protection. This combination of apparatus provides approximately 55 speed points for each fan.

In order to start up the fans it is only necessary to push a start button on the boiler panel which closes a latched-in relay. This places the fans in an operative condition. When the automatic combustion control calls for more draft the drums begin to rotate, the primary circuit breakers are automatically closed, the torque switches revolve until the motor starts up, and the drums are set on the desired operating point automatically. In the case of the induced draft fans, stack dampers are controlled by the same combustion control drive and a range of natural draft is utilized before the primary breakers close and the fans start. The speed range of induced draft fans is from 110 to 870 rev. per min. and on the forced draft fans the speed range is from 145 to 1170 rev. per min.

Primary air fans are controlled by manually operated secondary regulating resistance drums having 11 points, five of which are balanced. Their speed range is from 700 to 1750 rev. per min.

An elaborate system of interlocks has been provided to take care of emergencies in operating and to prevent situations which might cause an explosion of the powdered coal mixture in the boilers. Relay protection is provided to trip the fan circuit breakers on loss of 460 volts service. In case the two induced draft fans are tripped the two forced draft fans are automatically removed from the line to prevent the formation of positive pressure in the furnaces. If, at this time, the combustion control is still calling for mechanical draft, three of the four coal feeder motors are shut down. However, it is possible to operate the boilers at low ratings on natural draft and provision is made to prevent the shutting down of the coal feeders when operation is being carried on at low ratings. If the primary air pressure should fail three of the four coal-feeder motors are shut down and the steam aspirators are turned on. If positive pressure should occur in the furnace the forced draft fans and three of the coal-feeder motors are automatically shut down. Latched-in relays are used at the head of the various interlocking trains in order to prevent the shutting down of the fans in case of a failure of the d-c. relay supply circuits. The loss of control voltage will only prevent a change in speed of the fan motors, and will not cause them to shut down.

The coal feeder motors having an extreme speed range by means of automatic field control are direct current. Their bus is normally supplied by a 50-kw. motor-generator set with an emergency transfer breaker to operate in case of low voltage, throwing the load on to the main d-c. bus. The speed of these coal feeder motors is controlled by an automatic combustion control drive, which operates a gang of four field rheostats for each boiler. The motors are started and stopped by means of push buttons on the main boiler panels which control single step armature resistance starters. Interlocks have been provided as mentioned before to cut off three of the four motors in each group in case of trouble. These coal feeder motors are 5-hp., 250-volt, d-c., enclosed, and have a speed range of from 400 to 1600 rev. per min.

## BOILER FEED CONTROL

The 500-hp. boiler feed pumps are controlled by motor operated drums having 36 points and a speed range of from 1400 to 1750 rev. per min. The speed controls are arranged either for push button or automatic operation.

The automatic operation of each pump is controlled by the differential pressure between the pump discharge and the boiler drum. This differential, which is limited to a certain minimum, is varied approximately as the square of the load by a diaphragm on the regulator which is connected to the discharge duct of the forced draft fans. The process is selective by means of check valves in the case of the fan pressure and boiler pressure, so that the control is by the fan or boiler of highest pressure.

The 125-hp. condensate pumps have 24-point hand operated secondary regulating resistance drums with eight balanced points, giving a speed range of from 1400 to 1750 rev. per min. The 175-hp. circulators also have hand operated drums with a speed range of from 175 to 350 rev. per min. in eleven steps, five of which are balanced.

## CARBON CIRCUIT BREAKERS

Recent tests made by this company demonstrated that for low voltage, high current work, carbon circuit breakers and contactors performed satisfactorily in clearing the short circuits that might be imposed upon them at Gould St. From our point of view this was highly satisfactory, because such breakers and contactors are particularly well suited for inspection and maintenance. Being on open panel boards, heating or other troubles are readily discernible and contacts are easily inspected. Carbon circuit breakers are used exclusively on "essential" circuits—where interruptions must be reduced to an absolute minimum. Here it is necessary that a "latched-in" mechanism be used instead of depending on a holding coil, which is subject to failure. For the auxiliary generator, station service transformer, and other main feeders a type of circuit breaker was chosen with a mechanical trip-free arrangement, such that when closed in on a short circuit by remote control (solenoid operation) it would trip out the instant the short circuit was established. This feature of being trip-free throughout the entire stroke had to be developed especially for this job on the large 5000-ampere, three-pole breakers used on the station service transformers, and fan bus ties, although the smaller remote control and hand operated breakers were already available, so equipped.

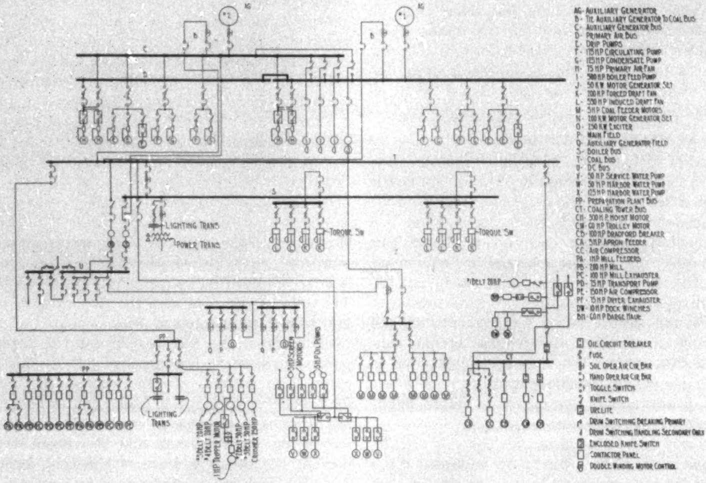
AG
LIGHTING TRANS
POWER TRANS
TORQUE SW
TORQUE SW
LIGHTING TRANS
AG- AUXILIARY GENERATOR
B- TIE AUXILIARY GENERATOR TO COAL BUS
C- AUXILIARY GENERATOR BUS
D- PRIMARY AIR BUS
E- DRIP PUMPS
F- 175 HP CIRCULATING PUMP
G- 125 HP CONDENSATE PUMP
H- 75 HP PRIMARY AIR FAN
I- 500 HP BOILER FEED PUMP
J- 50 KW MOTOR GENERATOR SET
K- 200 HP FORCED DRAFT FAN
L- 550 HP INDUCED DRAFT FAN
M- 5 HP COAL FEEDER MOTORS
N- 200 KW MOTOR GENERATOR SET
O- 250 KW EXCITER
P- MAIN FIELD
Q- AUXILIARY GENERATOR FIELD
S- BOILER BUS
T- COAL BUS
U- DC BUS
V- 50 HP SERVICE WATER PUMP
W- 50 HP HARBOR WATER PUMP
X- 125 HP HARBOR WATER PUMP
PP- PREPARATION PLANT BUS
CT- COALING TOWER BUS
CH- 300 HP HOIST MOTOR
CW- 60 HP TROLLEY MOTOR
CB- 100 HP BRADFORD BREAKER
CA- 5 HP APRON FEEDER
CC- AIR COMPRESSOR
PA- 1 HP MILL FEEDERS
PB- 200 HP MILL
PC- 100 HP MILL EXHAUSTER
PD- 75 HP TRANSPORT PUMP
PE- 150 HP AIR COMPRESSOR
PF- 15 HP DRYER EXHAUSTER
DW- 10 HP DOCK WINCHES
BH- 60 HP BARGE HAUL
OIL CIRCUIT BREAKER
FUSE
SOL OPER AIR CIR BKR
HAND OPER AIR CIR BKR
TOGGLE SWITCH
KNIFE SWITCH
URELITE
DRUM SWITCHING BREAKING PRIMARY
DRUM SWITCHING HANDLING SECONDARY ONLY
ENCLOSED KNIFE SWITCH
CONTACTOR PANEL
DOUBLE WINDING MOTOR CONTROL

FIG. 14—ONE LINE WIRING DIAGRAM OF A-C. AND D-C. AUXILIARY SERVICE FOR NO. 1 AND 2 UNITS

### 460-VOLT WIRING

Fig. 14 gives the wiring diagram for 460-volt auxiliaries. Separate operating buses are provided for the essential auxiliaries of each turbine and are supplied by the auxiliary generator. These buses are arranged in pairs with the ends overlapping so that the boiler feed pumps, primary air fans and coal feeder motor-generator set for each two units may, by means of double-throw knife switches, be operated from either bus. In addition each bus carries the circulator pumps, condensate pumps, and drip pumps of its own machine. It will be noted that the circulator and condensate pump feeds are arranged in pairs of one each. This necessitates the shutting down of only one motor of each class in case of a breaker tripping.

FIG. 15—VIEW OF STATION AUXILIARY SERVICE SWITCHBOARD

The essential auxiliaries are equipped with overload devices which function only on short circuits. In other words the circuit breaker trips or the CO relays are set to take the motor off the line only when the current exceeds the pull out torque value. Fig. 15 shows the 460-volt switchboard.

### STATION TRANSFORMERS

The station service transformers at present consist of three 1000-kv-a., 40-deg. cent. rise, 1250-kv-a., 55 deg. rise, or 1500-kv-a., one hr. overload rating single-phase oil-insulated self-cooled 13,200/460-volt transformers, connected delta delta. Relays are arranged so that an overload on this bank would trip off the coaling tower, the coaling bridge, and the preparation plant. The bank also has differential protection which trips the high tension oil switch as well as the low tension breaker, in case of internal trouble.

### COMMUNICATION

Communication throughout the plant is effected by a telautograph system having six stations, code calling by means of air whistles being used. There is also an intercommunicating telephone system which reaches strategic points in the entire plant as well as a number of Bell stations connected to the company's private branch switchboard for outside calls.

### INVESTMENT COSTS PER KW. CAPACITY

Throughout the design of the Gould St. Plant the object was to secure maximum reliability with minimum total costs per kw-hr. By total costs is meant not only operating labor and superintendence, maintenance, and fuel cost, but fixed charges on the investment. This criterion was used in the choice of apparatus, the cost of the apparatus being weighed against its ability to reduce production costs.

We give below a table of the actual cost of the first unit, and the estimated costs of three additional units; the estimated cost of the completed plant of 144,000 kw. being $88.26 per kw.

| | 1 unit (Actual) | 2 units (Est.) | 3 units (Est.) | 4 units (Est.) |
|---|---|---|---|---|
| 1. Investment cost as per Report of June 20, 1927 . . | $4,681,821 | $7,396,224 | $10,090,322 | $12,709,909 |
| 2. Capacity—kw. . . | 36,000 | 72,000 | 108,000 | 144,000 |
| 3. Cost per kw. . . . . | $130.05 | $102.73 | $93.43 | $88.26 |

The wide spread between the cost per kw. of the first unit and the cost per kw. of the completed plant is due to the many items included under the first unit, which are designed for the completed plant, such as, land, relieving platform for coal storage, coal handling, preparation plant, etc.

The capacities given in the above table are the net send-out capacity with four-stage bleeding.

Under two-stage bleeding conditions capacity is increased considerably and a net send-out capacity of 40,000 kw. is readily obtained and will be obtained in the event of need, for peak load conditions. Figuring this higher capacity the investment costs become as follows:

| | 1 unit (Actual) | 2 units (Est.) | 3 units (Est.) | 4 units (Est.) |
|---|---|---|---|---|
| 1. Investment cost as per Report of June 20, 1927 . . | $4,681,821 | $7,396,224 | $10,090,322 | $12,709,909 |
| 2. Capacity—kw. . . | 40,000 | 80,000 | 120,000 | 160,000 |
| 3. Cost per kw. . . . . | $117.05 | $92.45 | $84.08 | $79.44 |

The investment figures given include all expenses of every nature in connection with this plant, covering such items as preliminary engineering, old buildings used, interest during construction and during tuning up period, also a portion of the floating equipment of the company properly allocated to serve this plant.

### ACKNOWLEDGMENTS

Another paper is submitted at this meeting covering studies on design prepared by Messrs. Leilich, Follmer, Dannettel, and Fallon, to whom credit is given for the information in this general paper.

Mr. Penniman of the Company's staff is also presenting a paper on the operation of Gould St.

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## Discussion

For discussion of this paper see page 878.

# Design Studies for Gould Street Generating Station

BY F. T. LEILICH[1], C. L. FOLLMER[1], and R. C. DANNETTEL[1]
Member, A. I. E. E. Non-Member Non-Member

***Synopsis.**—Developments in the central station art have been so rapid within the last few years that many of the recent outstanding stations differ considerably in major elements of design.*

*In the following, are briefly outlined, high points of the analyses upon which the principal features of the Gould Street design were based.*

THIS paper covers briefly the various studies and investigations upon which the Gould Street design was based. Load studies clearly showed the need of additional 62½ cycle generating capacity in 1927. As a result, a single unit station of approximately 35,000 kw. was authorized. The major features to be settled before equipment specifications could be prepared and detail design work started were: steam pressure and temperature; number and size of steam generators; type of firing—stokers or pulverized fuel; heat cycle or working heat balance; the most economic design of condenser; auxiliary drive—electric or steam.

## STEAM PRESSURE AND TEMPERATURE

The general trend of pressure and temperature was upward, as shown by Fig. 1, which was plotted from the specifications of 85 stations. Operating records of other plants were studied and most of the new stations visited, at which time design and operating problems were discussed with the engineers. Essentially the problem was to select a pressure and a temperature that would result in maximum reliability and minimum total costs.

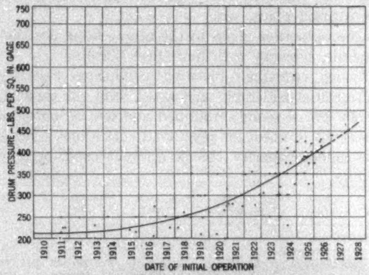

FIG. 1—TREND OF BOILER DRUM PRESSURE IN POWER PLANTS

Operating experiences with pressures up to 400 lb. and total steam temperatures up to 725 deg. fahr. were sufficiently extensive to show clearly that from the standpoint of reliability and operating difficulties these limits could be adopted for a conservative design. To obtain concrete figures showing the effect of pressure on costs and economy, detailed estimates based on a 40 per cent capacity factor, of a 250 lb.—700 deg. fahr., and a 400 lb.—700 deg. fahr. station were made. It is interesting to note that the estimated cost per kw. of the 250-lb. station was 4 per cent greater than for the higher pressure, and the over-all economy of the 400 lb. installation was six and one-half per cent better. Studies of relative costs of 600 and 700 deg. fahr. equipment showed that the improved economy of the higher temperature would justify the slightly increased cost of superheaters and added thickness of high temperature insulation.

A maximum drum pressure of 450 lb., with 725 deg. fahr. temperature at the superheater outlet was selected. This corresponds to 390 lb., 700 deg. fahr., at the turbine throttle. This temperature and pressure were selected after numerous conferences with the engineers of the various manufacturers and at the same time the possibilities of extension, using 1200 to 1500 lb. at the throttle of high-pressure turbines, exhausting at approximately 400 lb., into existing mains, were not overlooked.

## NUMBER AND SIZE OF STEAM GENERATORS

The boiler specifications called for working pressure in the drum of 425 lb. gage and total heating surface of 26,500 sq. ft. The bidders' guarantees covered operation up to 500 per cent rating, with 15 per cent $CO_2$, as it had practically been decided to use water-wall furnaces. The contract as awarded specified operation up to 520,000 lb. of steam per hr., which corresponds to approximately 550 per cent of rating, based on the total boiler and furnace heating surface. The trend of fixed and operating cost records of representative stations showed fixed costs as an increasing percentage of total costs and it was obvious that operating and kilowatt investment costs would be reduced if a small number of large steam generating units designed to operate efficiently over wide ranges of rating could be used. The experience up to that time indicated that water-cooled walls made it possible to operate at high ratings and over a wide range.

Load and operating conditions indicated that the

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[1] With Consolidated Gas, Electric Light & Power Co., Baltimore, Md.

*Presented at Regional Meeting of District No. 2, of the A. I. E. E., Baltimore, Md., April 17-19, 1928.*

turbo-generator units should have capacities of from 30,000 to 40,000 kw. each. Numerous plant layouts were made, and based on these the ultimate capacity of the station was tentatively set at four units, or approximately 140,000 kw. Estimates of investment costs for both equipment and structure showed distinctly lower costs for a design based on one boiler per turbine. The boiler and furnace designers were ready to build and guarantee performance on equipment on this basis. With the cross-drum type of boiler, which was preferred by the engineers, additional heating surface could be economically obtained by increasing the length of the tubes and making the tube bank the maximum width consistent with drums having no girth seams.

### TYPE OF FIRING

Many of the newer plants were using pulverized fuel, but it was not obvious that the advantages of this type of firing were such that it should be adopted without careful study. Operating engineers of plants using the two types of firing were consulted and the merits of each carefully weighed. Proposals on stokers and pulverized fuel were obtained and economic set-ups, covering both fixed and operating costs, prepared. Although pulverized fuel investment costs were higher, when the merits of the two systems—tangible and intangible—were carefully considered it was finally decided to adopt the central system of pulverized fuel firing.

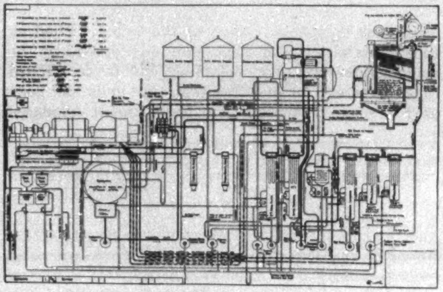

FIG. 2—FLOW SHEET REPRESENTING FULL-LOAD OPERATION WITH FOUR-STAGE BLEEDING AND 29 IN. VACUUM AT TURBINE EXHAUST

### HEAT CYCLE

A primary consideration was the selection of a heat cycle that would result in the lowest total cost, when both fixed and operating charges are included. Numerous set-ups were prepared, and economies calculated. Each showed that four-stage bleeding and air preheating would yield a greater return on investment than two or three bleeding stages combined with an economizer and preheater. The four-stage bleeding cycle has a further advantage of an approximate increase of 10 per cent capacity at only a slight drop in economy when operating under peak or emergency conditions with the two top-stage bleeders shut-off. In addition, for the machine under consideration a normal increase in capacity of approximately 300 kw. was possible, this being based on the power generated by the steam up to the first bleeding point, which steam by reason of limiting conditions of area in the lower stages could not have been used economically in the machine when designed for three-stage bleeding only. The foregoing advantages, and an economy increase of approximately 0.45 per cent by the use of four stages as compared to three, led to the adoption of the four-stage bleeder cycle.

Fig. 2 is a flow sheet showing the station heat balance for full load generation operating under 29 in. of vacuum.

The normal course of the condensate leaving the hotwell pumps is in order through the steam jet air pump inter-condenser, oil cooler, generator air cooler, tenth stage heater, after-condenser, eighth stage deaerating heater, boiler feed pump, evaporator condenser, fifth stage heater, and third stage heater to the boiler feed mains at a final temperature of 365 deg. fahr. Bypasses are provided individually for the oil cooler and the generator air cooler bank. Bypasses are also provided for the tenth stage heater and after-condenser as a group, and for the evaporator condenser and top-stage heaters as a group. Drips are cascaded from the top stage heaters to the evaporator condenser from which they are pumped into the condensate line leading to the eighth stage heater. Drips are cascaded also from the after-condenser to the tenth stage heater from which they are pumped into the condensate line leaving the tenth stage heater. The drip pumps are of the same type as the hotwell pumps, driven by slip-ring motors. Calculated feed water heater performances are given in Table I.

TABLE I
CHARACTERISTICS OF FEED WATER HEATERS

| Equipment | Lb. of water heated per hr. | Temperature deg. fahr. | | Water press. loss in ft. of water | Heating surface —sq. ft. | Terminal difference in deg. fahr. | Heat transfer in B. t. u. per sq. ft. per hr. per deg. fahr. mean temp. difference |
|---|---|---|---|---|---|---|---|
| | | In | Out | | | | |
| Third stage heater | 414,000 | 316 | 365 | 14 | 1,420 | 10 | 520 |
| Fifth stage heater | 414,000 | 279 | 316 | 15 | 1,565 | 7.5 | 515 |
| Evaporator condenser | 414,000 | 252 | 279 | 14 | 1,550 | 5 | 510 |
| Eighth stage heater | 340,000 | 204 | 247 | .. | .. | 0 | .. |
| After-condenser | 340,000 | 183 | 209 | 11 | 1,625 | 3 | 480 |
| Tenth stage heater | 310,000 | 92.5 | 182 | 11 | 2,000 | 5 | 455 |

Table II shows the calculated over-all B. t. u. per kw. hr. net station send-out. This is based on one boiler per turbine, auxiliary power 6 per cent of gross generation, over-all contingency factor 4 per cent, and throttle conditions 405 lb. absolute, 700 deg. fahr.

A turbine designed for non-bleeding operation was modified for bleeding conditions. Both the primary and secondary control valves admit steam to separate groups of nozzles which discharge through the buckets of the first wheel. This offered an advantage for bleeding at the third stage over designs where the secondary valve bypasses the first few stages. By increasing the steam flow areas in the first stages it was possible to admit sufficient steam for bleeding and still use the last stages as effectively in normal operation as for non-bleeding design. The non-bleeding machine was designed for 29 in. vacuum, but with the lower average vacuum of less than 29 in. expected at this particular installation, a greater quantity of steam is passed through to the condenser without increasing the leaving losses from the last stage and by reason of the power generated by this increased flow together with that generated by the additional steam admitted for withdrawal at the bleed points, the capacity of the turbine is considerably increased. A change from eleventh stage bleed-point to tenth stage gave an increase of 0.25 per cent in station economy.

TABLE II
B. T. U. PER KW. HR.—NET STATION SEND-OUT

| Load | 28 in. vac. | 28.5 in. vac. | 29 in. vac. |
|---|---|---|---|
| 35,000 kw. | 15,562 | 15,291 | 15,138 |
| 25,000 kw. | 15,103 | 14,707 | 14,356 |
| 15,000 kw. | 16,855 | 16,313 | 15,695 |

## CONDENSER

The average injection water temperatures throughout the year and the heat rejected to the condenser under various loads and exhaust conditions were the bases for the selection of the economic amount of condenser surface. Fig. 3 shows the relation between the exhaust temperature and the kilowatt increase in turbine output per degree of decrease in exhaust steam temperature. This method of analyzing turbine performance is described in the N. E. L. A. Prime Movers Committee Report on Turbines, December, 1926. The curve, (Fig. 4), shows the relation between injection water and exhaust steam temperatures for different load conditions and different areas of condensing surface. From the load duration estimate, injection water temperatures, and Figs. 3 and 4, the relative fuel economies of the different size condensers were determined. For these calculations, fuel cost was taken as 0.224 cent per kw. hr. In the final comparison, fixed charges were estimated at 16 per cent except on tubes, against which 30 per cent was charged, corresponding to about a 5-year life. It was found that 30,000 sq. ft. was about the maximum justifiable surface. This corresponds to 0.833 sq. ft. per kw. of generator capacity.

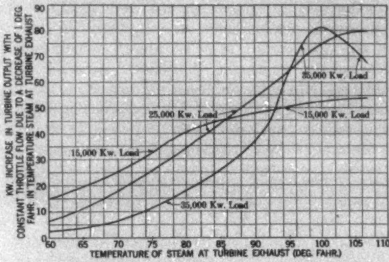

FIG. 3—GAIN IN TURBINE ECONOMY INCIDENT TO DECREASE OF DEG. FAHR. IN EXHAUST STEAM TEMPERATURE AT VARIOUS LOADS

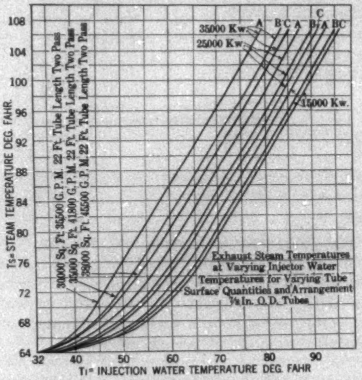

FIG. 4

It was essential that special effort be made to improve the purity of the condensate over that which ordinarily obtains in tide water plants; otherwise there would be no advantage in distilling the make-up, and the continuous operation of the boilers at high ratings would be seriously hampered. The point of attack was the leakage at the packed joints of the tubes. Floating tube sheets with rubber diaphragms as proposed by the manufacturers were not looked on with favor. Fixed tube sheets with tubes rolled in at both ends had been used in some instances in the Navy and it appeared feasible to adapt the principle to power plant service. It was found in tests made with an 18 ft. tube, set-up with the slight upward bow of 1½ in. at the center of its length between fixed plates, that repeated reversals of hot and cold water through it sufficient to give it the expansion between plates that would be encountered in service, produced no change in the structure of the metal of the tube, as seen under the microscope, and that the joints in the tube sheets remained tight. The tube was restrained in its vertical motion by the tube support plates, the holes in which were reamed to a special shape so that as the tube bends in expanding it has as much surface contact on the plate as possible. The shape of the expanded tube resembled a sine curve of about one and one-half cycles. The axial thrust of the tube against the sheets was as high as 425 lb. maximum, and at first it appeared that the staying of the sheets would be a difficult problem. On further analysis, however, the logic of eliminating all stay bolts presented itself, and the tube sheet layout shown in Fig. 5, in which all stay bolts are omitted and tubes rolled at both ends into fixed sheets, was adopted.

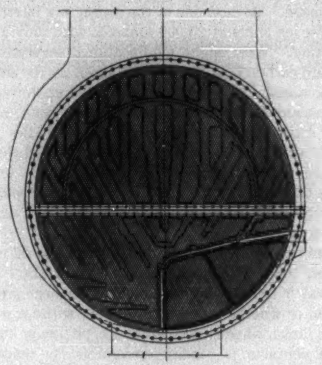

Fig. 5—Inlet End Tube Sheet Layout for 30,000 sq. ft. Condenser. (Note Question Mark Baffle for Guiding Water from Air Cooler Tube Surface to Outside Ring of Tubes in Second Pass

The manufacturer agreed to construct a condenser in accordance with this design with the provision, however, that the purchaser assume all responsibility for its success or failure.

### Auxiliary Drive

Electric drive was selected for the auxiliaries. Some of the factors influencing this decision were:

1. Elimination of small high pressure steam lines and exhaust lines.

2. Easier control of the heat cycle, as the steam requirements of turbine driven auxiliaries are not necessarily a direct function of the generator output.

3. Relatively high economy of shaft driven generators as compared to individual turbine drive. The steam per kw-hr. requirement for the auxiliary generator is the same as that of the main unit.

4. Flexibility and reliability of electric motors and their control.

The general tendency in auxiliary drive is shown in Table III, in which2 300, 440, and 220 volts were the prevailing a-c. potentials and 250 the prevailing direct current. Alternating current had been used in the greater number of installations and has the following advantages:

TABLE III
THE MAIN AUXILIARY CHARACTERISTICS OF CENTRAL GENERATING STATIONS

| Year of initial operation | Auxiliary voltage | | | Boiler feed pump drive | | | Circulating pump drive | | |
|---|---|---|---|---|---|---|---|---|---|
| | High 3000-2200 | Medium 660 -440 | Low 250 -110 | Turbine | Turbine and motor | Motor | Turbine | Turbine and motor | Motor |
| Other years | 0 | 1 | 2 | 2 | 1 | 0 | 3 | 0 | 0 |
| 1911 | 2 | 2 | 0 | 2 | 2 | 0 | 1 | 2 | 1 |
| 1912 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| 1913 | 0 | 3 | 0 | 0 | 3 | 0 | 1 | 2 | 0 |
| 1914 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| 1915 | 0 | 2 | 2 | 2 | 2 | 0 | 1 | 2 | 1 |
| 1916 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 |
| 1917 | 0 | 2 | 0 | 1 | 1 | 0 | 0 | 1 | 1 |
| 1918 | 1 | 3 | 0 | 2 | 2 | 0 | 0 | 2 | 2 |
| 1919 | 2 | 5 | 0 | 4 | 2 | 0 | 1 | 3 | 2 |
| 1920 | 3 | 0 | 1 | 3 | 3 | 0 | 2 | 2 | 2 |
| 1921 | 2 | 3 | 0 | 3 | 2 | 0 | 0 | 3 | 2 |
| 1922 | 2 | 0 | 1 | 0 | 3 | 0 | 0 | 1 | 2 |
| 1923 | 6 | 3 | 0 | 4 | 5 | 0 | 0 | 3 | 6 |
| 1924 | 12 | 3 | 0 | 6 | 8 | 2 | 0 | 2 | 12 |
| 1925 | 8 | 5 | 0 | 0 | 11 | 2 | 0 | 2 | 11 |
| 1926 | 6 | 0 | 0 | 1 | 4 | 1 | 1 | 1 | 4 |
| 1927 | 1 | 1 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |

Note:

1. Since practically every station has electrically driven auxiliaries and all use alternating current except for a very small portion of the axuiliaries, such as stokers, it was assumed that all auxiliaries are driven using alternating current.

2. In cases where more than one voltage is used for the auxiliaries it was assumed that the larger auxiliaries, using the major portion of the auxiliary power, used the higher voltage.

3. The fans were, almost without exception, driven by motors.

4. Boiler feed pumps listed under turbine and motor drive are usually motor-driven with turbine-driven stand-bys.

5. The numbers under each heading indicate the number of stations in that class for the stated year of initial operation.

1. Available up to a capacity far in excess of auxiliary requirements, if transformers are used.

2. Relatively low costs of motors and control for applications with small ranges of speed control.

3. Absence of commutators (excepting brush shifting motors) and elimination of sparking, which is highly desirable in a pulverized fuel installation.

The selection of the most economical secondary voltage required extensive calculations and estimates in which were considered motor, control equipment, and installation costs, for voltages of 2300 and 440 and speeds from 575 to 1750 rev. per min., also space requirements and such intangibles as reliability, ease of inspection, etc.

A voltage of 2300 showed a saving in copper for long runs, but was considered undesirable because of the impracticability of inspection of the control equipment under load. The higher voltage motors are standard only in the larger sizes, and their use necessitates a low voltage supply for the motors below about 50 hp.

Fig. 6 is a curve of standard 60 cycle, 900 rev. per min. motor costs as of 1926. For squirrel-cage motors, it is interesting to note that the cost curves for the two voltages, plotted with motor costs as ordinates and horse power rating as abscissas crossed at 138 hp. For wound rotor motors having the same synchronous speed as the squirrel-cage motors, the curves for 75 to 150 hp. showed the 2300-volt motor to be more costly over the entire range. From the standpoint of the motor cost alone the 2300-volt equipment is economically advantageous only for the larger size motors. For the range of sizes to be used in this station the 440-volt equipment was less expensive in practically every case.

Estimates of the cost of distribution cable showed that the cost per ft. is about equal at 100 hp.; below this the cost advantage was in favor of the 440 to 460 volts. Cable costs were based on 440-volt lead covered cable with 600 volt insulation, and 2300-volt lead covered cable with 4000 volt insulation. When motor, control, and cable costs were added to the value of the space requirements, the 2300-volt system proved to be more expensive than the 440 volt. The final selection was 460 volts, 3-phase, 62½ cycles.

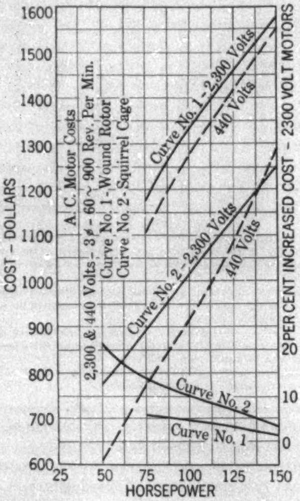

Fig. 6—Curves Showing Variation in Cost of Various Size Wound Rotor and Squirrel Cage Motors for 2300- and 440-Volt Service

For the auxiliary circuits it was desirable that oil breakers be eliminated and contactors or carbon breakers used. It was obvious that the circuit interrupting devices should be of sufficient capacity to handle short circuits, and in order to arrive at a basis upon which to prepare specifications a number of tests was carried out. The problem was put up to the manufacturers to furnish standard size contactors and circuit breakers rated up to 2000 amperes, which under test would handle repeated short circuits of not less than 20,000 amperes at 440 volts, 25 cycles, as the tests were to be made on 25 cycles. The contactors tested would not handle these currents, as after one or two operations the contacts had a tendency to "freeze." As a result of these tests, several of the manufacturers made modifications to their equipment, after which the contactors stood as many as five shots with practically no damage. In fact, one of the contactors interrupted about seven shots of 25,000 amperes with only a trace of pitting. With slight modifications, several of the standard carbon breakers handled about 20,000 amperes quite successfully. One feature insisted upon was that the breakers be non-closeable on short circuit, or trip free. Although the contactors handled the short circuits as well as the breakers, it was decided that the breakers were preferable to the contactors, for the reason that in case of failure of the holding coils, trip operated circuit breakers would not drop out, whereas contactors would.

Aside from the space requirements of the oil circuit breaker, there was the maintenance problem. There is no way of telling whether a breaker has been properly serviced or whether it needs attention, without removing the tanks, whereas with air break, pitting or burning of the contacts is readily discernible by inspection which can easily be made without dismantling the equipment. With a knowledge of the probable ultimate capacity of the station and the approximate maximum lengths of run and horse power of the auxiliaries, carbon circuit breakers were used on the auxiliary circuits with selected control equipment for handling the individual motor circuits. A control voltage of 250 volts, d-c., was used to eliminate the effects of a-c. disturbances on control apparatus and to insure quiet and more reliable operation of the contactors.

Auxiliaries were divided into two classes—essential, or those necessary for the uninterrupted operation of the turbine and boilers, and non-essential, or those such as pulverizing machinery—coal-handling plant and other equipment, a temporary shut-down of which would not interfere with the operation of the main unit and boilers. The essential auxiliaries are supplied with energy from the shaft driven alternator, the non-essentials from a bank of three 1000 kv-a., O. I. S. C. transformers. The arrangement is such that in the event of failure of the shaft driven alternator, the load is automatically transferred to the transformer bank. All auxiliaries are 460 volts, 3-phase, 62½ cycle, except the turbine room crane and the pulverized fuel feeder motors. These are supplied from motor generator sets, one running from the essential auxiliary bus, the other arranged to transfer automatically the load onto the transformer bank bus in the event of failure of the first motor generator set.

To reduce the voltage drop in the 460-volt bus, the copper in each phase was run in interleaved sections.

### COMBUSTION CONTROL

Based on the performance of stations operating with automatic combustion control, it appeared that monthly operating efficiencies that approached quite closely to test efficiency were possible. Proposals on automatic combustion control were analyzed, and calculations based on the guarantees and a study of performance in existing plants indicated that the increase in monthly efficiency would justify the cost.

On account of the wide range of speeds—8 to 1 on both forced and induced draft fans—double winding, 6-phase, secondary slip-ring motors were specified. A large number of speed points was necessary, and special control equipment consisting of drums and a motor-operated transfer switch for changing from the high to the low speed connection on the motor were installed. An excessive number of contactors would have been required to give the number of speed points specified. Also the cost of the control equipment using drums operated by the combustion control drive with provisions for manual operation and mechanical interlock between the drums was appreciably less than that of the contactor set-up.

## Discussion

For discussion of this paper see page 878.

# Operating Experiences at Gould Street Station

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*Synopsis.—This paper deals with experiences in connection with the starting up and the initial operation of a steam-electric generating station, located at Baltimore, consisting of large cross-drum, sectional header, water tube boilers fitted with water cooled furnaces which are fired by pulverized coal. The plant operates at 450-lb. pressure with 725 deg. temperature steam, the turbines being fitted for four-stage bleeding. All auxiliaries are motor driven, the power being supplied either from direct-connected auxiliary generators, or from the main station bus bars through step-down transformers. This paper attempts to describe the major difficulties that were encountered in placing the plant in operation and outline the methods used in their elimination.*

THE first cost of a power plant in any given location under the physical conditions existing at the site chosen, is largely a question of the fullest use of materials and equipment. This makes it desirable to use the smallest number of units of equipment of the largest permissible size, operated at the maximum allowable ratings. The auxiliary equipment must be carefully selected, with a view to maximum reliability, so as to permit of the installation of a minimum amount of spare apparatus. The installation of the equipment thus chosen, in order to use a minimum amount of space consistent with ease of access for operation and adequate maintenance, will result in the most economical balance between first cost and operating labor and maintenance costs. The actual manner in which this scheme has been carried out in the Gould Street Station of the Consolidated Gas, Electric Light & Power Company is described in two other papers.[3] It is the purpose of this paper to present some of the actual difficulties encountered during the initial period of operation.

### OPERATING PERSONNEL

The Gould Street plant represents our first experience in the burning of pulverized coal. For this reason, we were somewhat handicapped in the selection of an operating crew; especially so, since we considered it highly desirable to have as operators men who had been under observation for a sufficient length of time to satisfy us with regard to their fitness. Several months previous to the time that the first section of the Gould Street plant was scheduled to be ready for operation, certain men who were judged to be able to adapt themselves easily to the operation of pulverized coal equipment were selected from the operating organization. Also certain other men were employed and given some operating training at our Westport stoker-fired plant.

### COAL HANDLING EQUIPMENT

That equipment which we have classed as coal handling equipment consists of the coal hoist, Bradford breaker, barge haul and five conveyer belts, the second belt being provided with an airplane tripper for unloading to the coal storage yard, also with a hopper to receive coal reclaimed from storage. The pulverized coal transport equipment is considered separately.

Troubles which have developed in the coal handling equipment have not resulted in any great amount of inconvenience. Of major importance was the failure of some parts used in propelling the airplane tripper and its unloader belt, the drive being from the main conveyer belt by means of gearing and clutches. One of these failures resulted in a runaway condition with considerable damage narrowly averted. The weakness was inherent in the design and was obviated by changing the drive over to a cable haulage arrangement actuated by a separately controlled motor.

### COAL PREPARATION EQUIPMENT

While a hammer mill, which is herein designated as a secondary crusher, is located between the second and third conveyer belts, we really consider this equipment a part of the coal preparation equipment. With the original arrangement of plates and hammers the capacity of this hammer mill was such that coal was piled up at its inlet when the coal hoist was operated at capacity. Readjustments were made, not only because of the hammer mill's limited capacity with its original adjustment, but also because it was thought that with somewhat coarser coal some difficulties with our grid driers could be eliminated or at least alleviated. After these changes were made, the capacity was increased, but the drier difficulties were not helped to any great extent. It was finally decided to by-pass the hammer mill completely, which enabled us to get better flow through the grid drier with little arching of the coal but, of course, placed a heavier duty on the pulverizing mills.

A pulverized coal system handling wet coal is subject to many ills, and it is difficult to obtain proper flow at many of the points where gravity is the moving force. Very unsatisfactory grinding is obtained with wet coal; after the coal is ground, some of it forms a pasty mass and sticks at almost every conceivable point; a mucky

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[3] *The Gould Street Generating Station*, by A. S. Loizeaux, page 853. *Design Studies for Gould Street Generating Station*, by F. T. Leilich, C. L. Follmer, and R. C. Dannettel, page 866.

*Presented at the Regional Meeting of District No. 1, of the A. I. E. E., Baltimore, Md. April 17-19, 1928.*

mass very often collects in the mill, choking up the air passages; vent lines become choked; cyclone separator discharge lines become plugged; transport pumps and lines become plugged; the coal cakes in the pulverized coal bins; arches over the feeder screws at the boiler, causing burners to become extinguished; and even the burner pipes become so choked that in many cases it is necessary to take pipes down for cleaning, as the rapping on the pipe is often ineffective. There is also much difficulty from irregular feeding of the coal to the furnaces, which greatly reduces the furnace efficiency.

The steam-heated grid-type driers originally installed were found to be inadequate for our conditions. As already explained, the delivery of fine coal to the drier resulted in arching and inability to get the coal to flow through the drier. There was also additional trouble due to the pulling along of considerable coal by the air used to remove the moisture. A large amount of air is necessary and while it was put through a cyclone separator, the separation was incomplete, causing a considerable loss of coal. The coal recovered in this cyclone separator was discharged into the hoppers of the transport pumps. There was the additional objection that much of this coal was coarser than desired. Some of the drier grids were removed to better these conditions. While the feeding was bettered, the drying of course was less complete.

Furthermore, the amount of moisture removed was not so great as was necessary for the satisfactory milling and handling of the coal. Failure in this respect caused other means of obtaining the desired result to be considered. We believed that the most reasonable scheme would be that of drying the coal while in a finely divided state in the air circulatory system of the pulverizing mills, as it should give up its free moisture very readily. Due to the relative locations of the mill house and boiler room, it was not feasible to use stack gases for supplying the heat required, or to use the air vented from the mill system for primary air. Accordingly it was decided to heat the make-up air by means of high-pressure steam, so as to obtain the maximum temperature, thereby permitting us to supply the necessary heat with a minimum of air. This permits of using apparatus that is much more compact and reduces to a minimum the amount of fine coal that is lost in the vented air. The mill drier is not effective in drying the coal until it enters the mill and this, of course, does not help the flow of coal to the mill. High moisture, however, has caused no appreciable difficulty in feeding the mills, since the grid driers have been removed. The mill drying system is performing very satisfactorily and has practically eliminated the many annoyances incident to wet coal. In regular operating practise the mill drier has been successful in reducing the moisture content of the coal from 6 per cent entering the mill down to 1.7 per cent leaving the mill.

The air washer as originally installed for use with the grid type driers did not remove the coal dust to a sufficient degree. It was also inadequate when the mill type drier was put in commission. In order to obtain satisfactory removal, it was necessary to increase both the amount of steam and water used. At the present time, approximately 1150 lb. of steam and 2900 gal. of water are used per hour, with a dust concentration of about 0.8 grain per cu. ft. of air entering the washer, the amount of air handled being approximately 1240 cu. ft. per min.

On the whole, the pulverizing mills have performed very satisfactorily, although, of course, there is considerable wear of the grinding rollers and bull ring of the pulverizing mills, and of the blades and wearing plates of the mill exhausters. These mills, (designated by the manufacturer as of 20-tons per hr. capacity), have pulverized at an average rate slightly in excess of 24 tons per hr. each, the coal leaving the mill having an analysis about as follows:

| | |
|---|---|
| Moisture | 0.76 per cent |
| Volatile | 25.28 per cent |
| Fixed Carbon | 63.76 per cent |
| Ash | 10.20 per cent |
| Sulphur | 2.02 per cent |
| Amount through 200-mesh sieve | 74.2 per cent |
| Amount through 100-mesh sieve | 89.4 per cent |
| Retained on 40-mesh sieve | 0.4 per cent |

At times there has been some difficulty experienced due to coal hanging up in the cyclone separators or in faulty delivery to the hoppers of the transport pumps, because of improper functioning of the flappers of check valves or the choking of vent lines from hoppers to suction pipes of mill exhausters. One other difficulty was the collecting of a mucky mass of coal and water in the chamber of the mill that receives the air returned from the cyclone separator. A muck collecting pocket installed on one of the mills served to alleviate this condition somewhat. However, the better drying obtained when the mill-type drier was installed eliminated all trouble of this nature.

### Coal Transport System

There was considerable trouble with the operation of the pulverized-coal transport system when the plant became active. Most of the difficulties resulted in the plugging of transport lines which, being new and rough, were accredited with the responsibility for part of the troubles. The starting up of this system occurred during cold weather and this, in conjunction with the faulty performance of the driers was responsible, no doubt, for the greater portion of the plugging. Also, the size of the hoppers above the transport pumps was thought to be too small for even delivery to the screws of the pumps and partially responsible for the pumps plugging. Accordingly, they were increased in size by adding height with filler pieces having rectangular openings to conform to the hoppers. It was discovered that considerable water collected in the cylinders of the pumps after being shut down several hours. Keepnig the pumps drained was the logical answer to this difficulty. Increasing the air pressure on the nozzles of the pumps also helped to keep the boilers supplied with coal. Later, when the transport lines were worn smooth and the mill drier system was in service, trouble with the transport system practically disappeared.

Coupled with the difficulties of pumping the coal was the difficulty of the sticking of the transport line switching valves. This was alleviated somewhat by applying brass liners to the valves. This has not been an absolute remedy, as it is necessary to operate the valves frequently and even then, to dismantle them occasionally for complete cleaning. A careful analysis of the factors involved is now under way and it is hoped that this will result in eliminating any abnormal routine operation of the valves to prevent their sticking.

### PULVERIZING COSTS

The amount of power used in the grinding and transporting of the pulverized coal averages approximately 19.6 kw-hr. per ton of 2000 lb. The expenditure for the maintenance of pulverizing equipment has been approimately 13.9 cents per ton.

### BOILER ROOM

The greater amount of effort has been put forth in tuning up and making structural changes in the boiler room to approach or exceed design conditions. While efforts have been made to hasten the process, at this date, February 10, 1928, there are several matters that have not been brought to a satisfactory state.

At the outset considerable difficulty was experienced with poor feeding of the coal due to insufficient drying and condensation on the walls of the bunkers. It frequently became necessary to empty a bunker of the coal which would flow; then have men enter the bunker and scrape down the pasty masses of coal which cling the walls and arch over the feeder screws. This condition was eliminated almost entirely by the mill type drier when it was put in operation. Since our early experiences, No. 1 bunker has been covered with heat-insulating material and an investigation has been made on No. 2 bunker by forcing preheated air over the coal from one end to the vent at the opposite end to reduce the humidity of the air over the coal. The use of hot air results in less condensation on the walls, but also in an increase in the amount of coal lost out of the bunker vent. A combination of heat insulation with the use of hot air would probably give a still better feeding performance.

With the coal-feeding equipment originally installed, it was impossible to reach the maximum designed capacity, part of the fault being insufficient motor speed. However, sufficient coal could not be supplied after the motor speed was increased to that designated. New screws, having a considerably greater capacity, were furnished for one boiler. These screws caused flooding to take place at lower ratings, resulting in very dense smoke and, in one or two cases, in the loss of much coal to the ash hoppers. Also, these screws had so much capacity that it was considered advisable to abandon them and hob out the original screws. Flooding also took place on these modified screws and to eliminate this, spring-loaded disks were applied to the discharge end of the screws to provide a uniform resistance to the coal being fed. These very successfully reduced the pulsations experienced with the feeders having greater capacity than the original.

The controls of dampers in the various ducts were originally unsatisfactory, in that it was possible for sudden changes to occur if the hand slipped on the operating chains. In the case of the primary air system, a damper got out of control and was responsible for an explosion occurring in the furnace of number one boiler, this explosion resulting in bulging of the steel casing and the bending of several side-wall tubes. By applying worm wheels and sectors to these dampers, the control has been made positive and easier to manipulate.

In order to guard against future explosions displacing the furnace sides, a horizontal steel buckstay was applied around the middle of the furnace for additional strength, as it was assumed that the air and gas passages should furnish sufficient relief for the expansion of the products of combustion resulting from such explosions. The boiler control, also, was provided with some features to eliminate some of the provoking causes of explosions. Furnace contactors were provided to trip out three of the four coal feeder motors per boiler on the occurrence of excessive furnace pressure. Primary air pressure contactors were arranged to trip out the same three feeder motors and to turn on the steam to the burner aspirators on the occurrence of low primary air pressure. The forced draft fan control is arranged to trip if both induced draft fans are tripped. Since these modifications have been made, no occasion has arisen necessitating their functioning.

Changes have been made in the burner design with respect to what is termed the tertiary air, *i. e.*, the heated air which is forced downward around the burner nozzle. These changes have been made with the idea of producing a longer downward sweep of the flame with less and hotter primary air. The present indications are that the new arrangement is very beneficial.

Experimental observations were resorted to in order to obtain a better distribution of air across the furnace. The number of port openings in the front wall was substantially reduced which, by proper selection of the ones to be closed off, improved the distribution, produced greater turbulence, and also made available a higher tertiary air pressure. It was then possible to exercise more control over the tertiary air.

The spring-loaded dampers governing the flow of secondary air to lanes in the front wall have performed unsatisfactorily at times, and it has been necessary to provide hand-control to those governing the air admitted by the four uppermost lanes. It is now considered desirable to have all of the spring-loaded dampers operated by hand from the main boiler floor.

Some difficulties have been encountered with slagging of the lower rows of boiler tubes. This slagging usually occurred after the boiler had been carrying about 400 per cent rating continuously for 48 hours or longer. Little trouble was experienced when less load was carried at night than in the daytime, and it has been noticed that much slag which had accumulated when operating at high rating, fell off when the rating was reduced for several hours. On one of these occasions when a high rating had been maintained for longer than 48 hours, an attempt was made to cause the slag to drop by increasing the excess air, but this apparently had little effect. A shot gun was fired at the slag but was found to have negligible effect. One proposal advanced to prevent this trouble was to remove every other tube in the bottom row of boiler tubes, which would mean that the spacing of this bottom row would then be approximately the same as that of the water screen and, consequently, slagging would be greatly reduced. The boiler manufacturer has recommended against removal of these tubes and, instead, suggests removing every other tube in the lower row and installing deformed tubes which would have a drop of 7 in., thereby accomplishing the same result with no loss in heating surface.

The air heaters are arranged with straight vertical flue gas passages and U-shaped air passages, the air entering and leaving on the same side of the heater, thereby providing very unequal resistances to flow in the air lanes. The result of this was a wide spread in the air temperatures leaving the air heater, there being about 200-deg. fahr. temperature difference between the top and bottom of the duct discharging air from the heater. A deflecting-type baffle was applied to guide the air towards the lanes having the longer paths. Another scheme which was also experimented with, consisted of adding resistance at the air inlet to the shorter paths, the increased resistance to flow of air being obtained by the application of metal strips. The two schemes did materially help the situation and were of about equal merit, although neither attained the desired result. Both schemes are objectionable from the standpoint of power loss caused by the increased duty placed on the forced draft fans. The air heater manufacturer is now taking necessary steps to improve the performance of this apparatus.

The bearings on the primary air and induced draft fans are of the ring oiled type provided with an integral oil cooler built into their bases to eliminate the necessity of separate oil pumps for the circulation of the oil and also to permit the use of harbor water for cooling. There was some trouble from the leakage of water into the oil reservoirs which was eliminated by a slight change in the design of the coolers.

The induced draft fans are of the plate-type because of the high duty imposed by the requirement of handling 135,000 cu. ft. per minute of 450-deg. fahr. gases against a static head of 15.8 in. of water. These fans have given excellent service except for some slight vibration due to the bearing pedestals being somewhat light. This has been corrected by the application of bracing. Two failures of an induced draft fan motor have occurred, the reason for which cannot be ascribed to overload or faulty control. The first failure was of the north motor on No. 2 boiler. This motor was removed for repairs and was replaced by No. 1 south motor. The repaired motor, when returned, was placed at the former location of No. 1 south motor. Soon after this, the repaired motor failed. This motor was again repaired and has been operating satisfactorily for some time.

Five failures of fin tubes constituting the back furnace wall have occurred. These tubes have all failed in the same manner and almost at the same spot; namely, the outside of the top bend of the rear wall tubes near the sides of the furnaces. In one case, a large bulge was noticed before an actual rupture occurred. The water circulation is to be investigated to determine whether or not there is considerable difference in rapidity of water circulation in different parts of the back wall. The obtaining of this information will no doubt make possible a satisfactory analysis of this condition.

Because of the high rating for which these boilers are designed, it was necessary to supply two 6-in. feed-water regulating valves. It was found that the thermostatic tubes of the feed-water regulators were not sufficiently powerful to operate the valves properly. New pistons were designed by the manufacturer in an effort to reduce the friction which was apparently caused by water flow, since the friction was quite low when no water was flowing through the valves. The new pistons did not prove entirely satisfactory and attention was directed toward the use of hydraulic power utilizing the thermostatic tube to actuate only a pilot valve. As an experiment, one such valve was fitted with a hydraulically operated relay mechanism. The operation was so much more satisfactory that the manufacturer equipped all the regulators with hydraulic operating mechanisms. With this arrangement, there is the additional advantage that the slope of the thermostatic tube can be lessened to speed up the response of the regulator.

Soon after starting the plant, it was determined that the moisture content of the steam leaving the boiler drums was higher than desirable. The boiler manufacturer has developed and installed a new type of baffle which has produced excellent results. The curves in Fig. 1 show, graphically, how great the improvement has been. This improvement should be of much benefit in the maintaining of cleaner surface on the interior of the superheater tubes, since the moisture, of course, carries solids in solution. It also will reduce the duty on the superheater for a given temperature of steam leaving the superheater.

The plant has operated for a large portion of the year 1927, with lower superheat than the design value. It was held advisable to delay the raising of the steam temperature until other apparatus which would influence the result had been tuned up. Just recently the baffling of the gas passage at the superheater has been changed to give the desired steam temperature. The remaining feature to be reckoned with is the pressure drop of the steam through the superheater, this being approximately 35 per cent higher than expected. Since it reduces the pressure available at the turbine throttle with a given boiler drum pressure, this pressure loss results in a diminution of turbine capacity, thereby limiting plant capacity. The manufacturer has considered the possibilities of reducing this pressure loss to the desired value and is taking the necessary steps to eliminate this difficulty in the near future.

As to the matter of combustion control, several difficulties were experienced in the burning out or breaking down of coils and grounding of wiring. Discharge resistances were provided to lessen the inductive kick from the coils, and wire with varnished cambric insulation was used in the control boxes to withstand the oily atmosphere. Some trouble has also been experienced with the motors in the control boxes grounding, the grounding usually occurring on the brush rigging. Now it is planned to arrange the drive so that the motors may be placed outside. Some gears have been broken, a key sheared, and chains broken, the chains being used to interlock the various drum controllers of the fan motors. Because of the necessity of controlling two 550-hp. pole-changing induced-draft fan motors and two 200-hp. pole-changing forced-draft fan motors, all of the wound rotor induction type, the drive necessarily has quite a task to accomplish, the pole changing feature of the motors contributing some complication on account of the necessity of providing overlap.

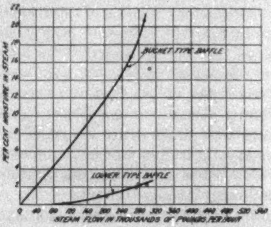

Fig. 1—Steam Quality Gould Street Boilers

The combustion control is normally set to maintain 15 per cent $CO_2$ averaged across the section of the boiler gas outlet. This setting is interfered with to some extent by a variation in feed water temperature. This is particularly so if the two higher pressure feed-water heaters are cut out of the circuit at 20,000- to 35,000-kw. load on one boiler. An attachment has been designed to quickly correct the meter for this condition and is being installed. The combustion control which we have installed is not suitable for quick changes in load, this having been demonstrated several times. It is our usual practise to operate on semi-automatic control for the quick changes in load which can be anticipated, such as the noontime drop and the morning pick-up.

There are eight 4½-in. high lift safety valves on the drum, and two on the superheater outlet of each boiler, each drum valve having a relieving capacity of 52,500 lb. per hr. and each superheater valve 35,000 lb. per hr. While these valves have not been tested for relieving capacity, two occasions have arisen when the entire plant load has been lost in which the safety valves relieved a total of 380,000 lb. per hr. satisfactorily. One of these occasions was when an air drill penetrated the high-voltage leads from the main generator, causing the differential relays to trip out the oil switch and field breaker, the other when the throttle valve of the main unit became unlatched. The leakage and maintenance of these valves has been very slight and, as a matter of fact, has not been any higher than has been experienced at the Westport plant on 200-lb. pressure service.

There are three ash gates per boiler, 41 in. by 56 in., actuated by oil operated cylinders which at times have refused to move due to friction, distortion, and failure of cast iron plates. In certain places where two ferrous materials rub on one another, one of them has been replaced by non-ferrous material, clearances have been increased, and the cast iron support plates have been reinforced with steel. The result has been almost complete elimination of the sticking difficulties.

## TURBINE ROOM

Since No. 1 turbine has been placed in operation, few troubles have been experienced with it. One of these has been the sticking of the primary control valve stem. This stem was made of "Ascoloy" and slides in a Monel bushing. These two metals apparently are not very satisfactory for sliding contact. The Ascoloy stem was replaced with one of medium carbon machinery steel and the bushing enlarged to give a greater amount of clearance, the packing being relied upon to serve partially as a guide. It is contemplated that an Ascoloy stem will again be used but with a cast iron bushing so contained in a steel cage that the cast iron will not be able to break up and go through the turbine. One difficulty which was experienced soon after the turbine was started up the first time was undesirable vibration of the throttle and control valves. This was remedied by the elimination of undue play at certain points and the redistribution of the weight of the pipe, control, and throttle valves among several hangers.

The main condenser, while of somewhat radical design in that the tubes are rolled into the tube sheet at both ends, has given but little trouble. The noticeable leaks which have occurred have been very few. In spite of the fact that the circulating water is high in salt content, we have been able to maintain the solids in solution in the condensate at a very low value. Computations made before the plant was put into commission indicated that if the leakage was as high as usually obtained with packed tube condensers, it would be necessary to blow down the boilers very frequently, or continuously, in order to maintain the boiler water concentration at as low a value as was considered desirable. The following figures are indicative of the purity of the condensate as usually obtained:

Total solids.......... two parts per million.

Electrical Resistivity..1,000,000 ohms per cm-cube.

While the dip cells used in determining the electrical resistance of the condensate are subject to erratic behavior at times, the electrical resistance characteristic has been of great help in showing relative performance, because of the rapid change in resistance for a small change in the amount of leakage. Only one leak of consequence has shown up, this one apparently being due to a condenser tube not being rolled in at one end, the flare serving to keep the leakage down for a long time.

The circulating pumps originally furnished required too much power because of the water quantity pumped exceeding the design value and, in order to lessen the load on the motors, it was decided to turn down the impellers.

One trouble which has been had with the steam jet air pump inter-condenser has been the erosion of tubes from the discharge of steam from the pipes used to vent some of the bleeder heaters. Some tubes were removed and a baffle installed to decrease the velocity of the steam hitting the tubes.

The difficulties experienced with the closed bleeder heaters has been confined mainly to those under boiler feed pressure, the most annoying one being the leaking of gasketed joints. Some of this was a result of poor machining. Re-machining and the use of different gasket material has eliminated this annoyance almost entirely. One other source of annoyance has been the leaking of a porous, cast steel, water box which is to be replaced by the manufacturer. The eighth-stage bleeder heater is of the deaerating type and has given no operating troubles, and has delivered water having less than 0.05 cu. cm. per liter of oxygen.

As originally furnished, the evaporator, while its capacity was all that was expected, did not produce a distillate measuring up to the standard required. Considerable experimental work was required before this standard was attained. We were fortunate during this time in having a boiler operating in the old plant supplying steam for heating purposes. Thus, the heating boiler acted as an evaporator and the heating system as an evaporator condenser. The quality of the water obtained in this manner was good, and the amount was great enough for make-up purposes. The changes in the design of the evaporator were completed at about the time that the heating season ended. The evaporator is now producing water of following quality:

Total solids.......... 3.4 parts per million.

Electrical Resistivity..227,000 ohms per cm. cube.

With low condenser leakage and water of this quality, we have been able not only to hold the boiler water concentration to a low figure but have not been required to blow down the boilers at all on account of concentration, the concentration not having exceeded 500 parts per million.

While the boiler feed pumps are boiler auxiliaries, we are treating them under the head of turbine room equipment, since they are actually in the turbine room and are connected in between the low- and high-pressure bleeder heaters. The motor-driven boiler feed pumps have given but little trouble structurally. On one occasion there was a cessation of pumping which appeared to be due to vapor binding. This was ascribed to hot water discharged from the evaporator condenser drip pump being fed to the suction side of the boiler feed pump. While there was an economic advantage to the scheme from the standpoint of heat efficiency, it was considered to be outweighed by the demand for safe operation and, accordingly, this water was delivered to the eighth stage heater. Since then no further trouble of this nature has occurred. A shifting of the impellers and balancing drum occurred on the emergency steam driven boiler feed pump. This was apparently due to the wearing sleeves turning enough to allow the shift to take place. When repairs were made these sleeves were driven up hard and locked so that this trouble is not expected to occur again.

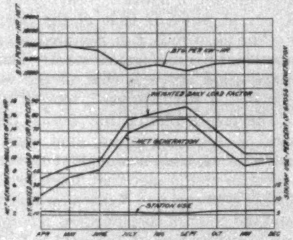

Fig. 2—Monthly Performance of Gould Street in 1927

### Over-All Performance

Whereas the plant delivered power to the bus for the first time on January 4, 1927, the amount of generation for the first three months was comparatively small, because of the decision to concentrate attention on those details which most affected the dependable operation of the plant. For this reason, these three months have been neglected in drawing up Fig. 2, which graphically illustrates the amount of generation per month, the average weighted daily load factor and B. t. u. consumption per kw-hr. of net sendout. The amount of generation reflects not only the tuning up of the plant but also the manner in which steam generation at Baltimore is affected by the river flow at the hydroelectric plant of the Pennsylvania Water and Power Company from whom we purchase quite a considerable amount of power. Two curves are shown on Fig. 3, one of which is that of the predicted performance of the plant in B. t. u. required per net kw-hr. of station sendout plotted against weekly load factor in per cent; the other curve is that of the weekly performance in B. t. u. actually used, plotted in the same manner. The points plotted for actual performance show quite a wide variation, not only because of the changes being made in the plant during the year, but also because of the fact that there are large coal storage spaces between the point at which the coal is weighed and the point of consumption, a comparatively small error in estimation of the coal in these spaces causing a much larger error in the consumption figures, the greatest error occurring when the consumption is least. It is expected that the installation of automatic coal scales to weigh the coal entering the mills will greatly decrease this error, since the effect of an error in the estimation of the raw coal bunker will be eliminated from the result, the pulverized coal bunkers then being the only storage space affecting the accuracy of the consumption figures. The monthly figures are somewhat more accurate since the amount of coal used is about four times larger and the error introduced by bunker estimates is thereby made one-fourth as much. It is expected that the predicted performance will be approached very closely.

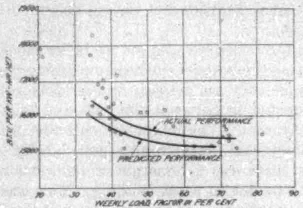

Fig. 3—Relation of Actual to Predicted Performance for Gould Street in 1927

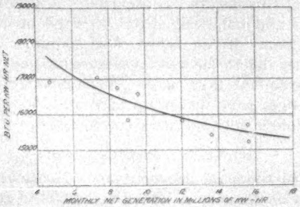

Fig. 4—B. t. u. Required for Various Monthly Outputs at Gould Street in 1927

From this outline, it is apparent that the plant has been subject to the usual minor changes and adjustments during the initial period of service. None of the troubles experienced was unsurmountable and all can be traced to the fact that most of the equipment affected was of the largest sizes that were obtainable, operating in many instances at rather high capacities. This introduced some problems that were entirely new, it being necessary for the manufacturers supplying equipment to do a certain amount of development after their apparatus was placed in service. While such a procedure is necessarily slow, it is felt that the manufacturers affected have made a very satisfactory record in solving their individual problems and in making necessary changes and connections.

The actual performance has approached fairly close to the anticipated, and it is apparent that, when the air heater performance is improved and the effect of the recent increase in steam temperature is realized, the anticipated performance will at least be met and possibly slightly bettered.

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## Discussion

### THE GOULD STREET STATION

(Loizeaux, Leilich, Follmer, Dannettel, Penniman, and Quarles)

Baltimore, Md., April 18, 1928

**A. G. Christie:** There is a number of interesting features in connection with the Gould Street plant.

In the first place, this is the first large American station that has been built on the basis of one boiler to one turbine, and the performance has been quite satisfactory. It is not necessary to have many spare boilers as in some of the older stations. It is quite probable that in new station designs Gould Street's arrangement will be followed.

Another factor of interest is the steam turbine, in which capacity for size of frame is somewhat larger than has been common in the older stations. In other words, for a given size of turbine casing a larger output is obtained than would have been the case a few years ago. This, of course, gives a greater capacity in kilowatts for a given size of installation.

The use of condensers with rolled tubes at both ends is a decided advance. That construction was used in Europe quite a number of years ago but with very short tubes and not with the tube lengths used at Gould Street. As has been pointed out, it was necessary to run a number of tests to determine what would happen to longer tubes and how their expansion could be cared for in order to have the condensers operate satisfactorily.

The type of feed-water heater used is also unusual and apparently quite an advance over former types. The hairpin vertical type of heater takes up little room between the turbines themselves. It is easier to get at than some of the older types.

The air preheaters occupy a large volume. Larger and larger air preheaters will undoubtedly be used as stations grow in size, particularly since their advantages have become recognized.

In Fig. 3 of Mr. Loizeaux's paper, the turbine room is apparently outgrowing the boiler house. By the time the four machines on the present program are installed, the boiler house will be considerably smaller than the turbine room. That suggests the possibility that larger turbines will be required for later units. Some plants have adhered to the system of having equal sizes of turbines throughout the whole station, but when the possibility occurs of getting extra kilowatts in the same space, it is pretty hard not to add the larger units.

**L. W. W. Morrow:** I can say whole-heartedly that this is the best group of power-station papers I have ever listened to at the engineering meetings, in that the authors have very frankly told all their troubles and difficulties in connection with the installation and operation of a new power station. Sometimes there is a defensive league, I call it, among engineers whereby everything they do is perfect and they never admit that they could have made an error. It stands to reason that the engineers in this country today are largely responsible for the reductions in the costs of power. It stands to reason that in departing from past practises and in making the great economies that have been made in the last five or ten years in power production, there must occur some errors. There must occur some pioneering engineering developments, and to get full advantage of experiences with new things it is really worth while for the engineers to talk frankly about the new plants.

There are one or two questions that arise in my mind. The use of automatic equipment is to improve station economy and reduce station labor charges. My first question is in regard to the operation of automatic boiler-room control; does it work well? The second question is about labor. How many men per shift are used in this station; and what degree of skill is required for maintenance and for operation? Another question that comes to my mind is the use factor that you can expect out of a one boiler one turbine combination. Are the turbines and boilers equal in reliability from a service standpoint?

The station game today is developing rapidly. We are working water and materials to the full degree they can be worked. The power engineer has to think in terms of basic physics, metallurgy, and chemistry and must be ready to use other fluids and gases than water and air in order to meet the demand for reducing power costs.

**H. C. Sutton:** In building this plant the engineers, in selecting every piece of apparatus, have taken into account the first cost, interest on the investment, and operating cost, to give us the lowest annual cost.

I note that one feature of the design of the station is rather conservative. It certainly is conservative to select a boiler pressure of 450 lb. I might say that we are interested in the design of a station now to be located at Deepwater, where we will have 1380-lb. boiler pressure.

Another feature that is of interest and unique, is the very large boiler and the admirable design of one boiler per unit. I think that is worth considering in future station design.

Another conservative feature is the low voltage for the station auxiliaries, 440 volts. We, in our recent stations, have selected 2300 volts and 440, except in the smaller stations where we have used 550 volts. Of course, that is a matter of economy, but it has this particular thing to recommend it in design; with the use of 440 or 550 volts you largely limit or eliminate the use of oil circuit breakers which are necessary with 2300-volt auxiliaries. So there is a gain in using the air-type breaker for station auxiliaries that is a very material one, particularly where you have group buses located at various advantageous points throughout the station.

The preliminary design of the Deepwater Power Station to be located opposite Wilmington is interesting. In that station there will be three 12,000-kw., 1200-lb. units, one of these units being used for a power company which will take the steam and also take the electric load from this generator. The other two 1200-lb. units will be the high-pressure units for the two main generator units of the station, the low-pressure unit being 41,000 kw., making a total of 53,000 kw. per unit. The only boiler pressure will be the 1380-lb. boiler pressure, the steam merely going back to be re-heated before going to the low-pressure unit.

**R. L. Thomas:** An outstanding feature of the Gould Street Plant is the unusual amount of attention given in design to what has recently been called "dollar efficiency." Other plants have been built during about the same period with lower fuel rates, but in considering those rates there should always be taken into account the cost of the corresponding equipment.

One question occurs to me. The Gould Street loading is such that there has been considerable "banking" at regular intervals throughout long periods. Information regarding banking experience might be of interest, for example, as to how boiler pressure is allowed to decrease during long and short banks, what intermediate firing is done, etc.

**J. C. Stott:** There is one feature to which I wish to call attention,—that is, the physical layout of the plant itself and of the apparatus in the plant. The plant has been built on about as small a piece of property as is possible without sacrificing any of the operating problems. The outstanding feature in the development of this property was the fact that it was so close to our load centers. The conditions there were very unsatisfactory in so far as foundation was concerned. The foundations, caissons, and footings for the various structures required special considerations. We have made a very economical plant layout when considering the many difficulties.

**F. O. Schnure:** I want to ask the authors if they have found it necessary to use all of the 53 points on the induced-draft fan control. Another question is—what method is used in grounding the generators, through reactor or resistance?

**M. M. Price:** Reference has been made in the discussion to the conservative design of this station. From the point of view of 1928, the design is conservative, but the plant was designed and purchased in 1924 and 1925 and the boilers were among the first Babcock & Wilcox boilers, if not the first, to be built for a pressure of 450 lb. with riveted steam drum 60 in. in diameter and with tubes 24 ft. long, and the amount of steam which it was planned to generate in each unit was considerably in excess of the ratings usually considered. The rating demanded of the boilers was so in advance of the practise at the time the boilers were designed that it necessitated redesigning the steam baffles in the drums. This redesign was only carried out through the hearty cooperation of the operating engineers and has led to a distinct advance in securing dry steam at high ratings.

Boilers of higher pressures were considered when the plant was designed but the data on stations designed for such high pressures were not sufficient at that time to justify the selection of a higher pressure, especially when consideration was given to the load conditions under which the station was expected to operate, which conditions still exist.

**A. S. Loizeaux:** In answer to Mr. Schnure's question, I would say that our Gould St. neutral is solidly grounded. We have recently put a ¾-ohm reactor in the neutral of our 25-cycle system and in the course of time we may do the same thing in our 60-cycle system to reduce the destructive current in the event of short circuits.

Professor Christie was very modest in his discussion. He was called in consultation on a good many matters while we were designing the Gould St. Power House and due to his wide experience in the design of plants in this country and his knowledge of European power houses he was of real help in the design of the Gould St. Plant.

The designing was done in our own engineering department and drafting rooms. The company's construction forces carried out the work. Contractors were called in for a few of the larger elements of the work. One of the more interesting elements was the caisson foundations required. The Foundation Company of New York was employed to obtain the benefit of their experience and use of their supervisory talent. The caisson foundations under the power house are sunk to 50 ft. below mean low water. The caissons supporting the coaling tower were constructed on shore, like boats, and floated out into place, then sunk and lowered to minus 50 ft. with the open method. Air was then put on the caissons and they were sunk minus 70 ft. with the compressed-air method.

In connection with the water walls of the furnaces, it was unknown what would happen at very high capacities with reference to the production of smoke but we find that there is no excessive smoking at the higher capacities that we have carried. This fact is very fortunate and permits large capacities and overloads on boilers. Mr. Price of the B. & W. Co. and other agents of manufacturers gave us excellent cooperation in the design and construction and entered into the problems involved in a way that insured their proper solution.

**A. L. Penniman, Jr.:** All of the difficulties experienced in this plant were confined to apparatus that differed in one or more points from equipment for similar purposes that has been in general use. For instance, the relatively poor quality of steam delivered to the superheater was brought about by using drum sizes and baffle arrangements which were normally used in boilers having 20-ft. tubes, and increasing the length of the tubes some 25 per cent. This means that the steam-to-water ratio at the outlet end of the tubes is necessarily very much higher, the velocities are accordingly higher, and the problem of separation in the drum becomes increasingly more difficult. In addition to this the boilers are arranged with furnaces which will permit of their being operated at relatively higher rates of evaporation than has been the general practise.

One question that I had anticipated would be raised in the discussion of this paper, and which would seem to be an entirely logical one is: "Why, after 15 months of operation, do we still have some of these difficulties that have not been ironed out?" This is due in part, at least, to inertia. In the first place when we get into trouble it takes some time for the operating men to form an opinion, after which the chances are probably 5 to 1 that the designing engineers do not agree with them and additional time is spent in the attempt to find a common ground. It is quite probable that the manufacturer is not going to agree with the compromise which we have reached among ourselves, so that additional time is required to arrive at some preliminary decision which frequently does not lead to a correction of the trouble, due to the fact that while we may think we know the physics and mathematics of a lot of these problems, we usually find after we get the final solution that there were many unknown factors. However, we must remember that the plant is doing substantially what it was designed to do. The figures in the curve of the paper were made before the steam temperature was raised. The air heaters have failed to meet the anticipated performance given by the manufacturer simply because laboratory experiments indicated higher rates of heat transfer than we have been able to obtain in practise. At present there seem to be very definite indications that the heat lost by radiation from the steam generating units is greater than was anticipated. On the other hand the heat-absorption rate of the boilers is apparently somewhat better than we had anticipated so that the curve, which shows a variation of about 2½ per cent from the designers' anticipated results, can be accounted for as being due to poor performance of the air preheater and to low steam temperature.

Another question that I had anticipated is: "What conclusions have we been able to draw from the operation of this plant that might guide us in future additions or in the building of another plant?" In the main there are three general points; one is, if you are going to use pulverized coal prepared by a central system, do not try to start up in cold weather. The humidity is so much higher in cold weather that the tendency to gum the mills transport system, and ground-coal bins, is very much greater than in the summer, and is very likely to be further aggravated during the time necessary to get the coal-drying apparatus tuned up. We had numerous cases of the plugging of transport pumps and transport lines, the mudding up of the return air lines from the cyclones to the mills, and the mudding up of the mill cyclones. The switching valves in the coal transport lines stuck frequently. The furnace feeder screws mudded up and the coal arched over the throat of the feeders. At times it was hardly possible to deliver enough coal to the furnace to keep up steam pressure on the boiler. As soon as we were able to dry the coal properly all of these difficulties disappeared.

Secondly, a great deal depends on the proper method of drying coal. Our experience with grid driers was most unfortunate. As a matter of fact they simply refused to dry at all, and in addition so impeded the flow of coal to the mills that it was necessary to remove a large percentage of the grids in order to get coal through them at a sufficient rate. We have now been using the mill-drying scheme for some five or six months. We are feeding air heated to slightly less than 400 deg. fahr. into the mill with the return air, and venting a comparable amount of air from the system at the air-outlet side of the mill cyclone. There have been no troubles from this system. The reduction in temperature of the air is very rapid due to the evaporation of the moisture in the coal. Apparently the air temperature drops from 400 deg. fahr. to less than 165 deg. fahr. in the first 12 or 14 in. of travel of the air, while the temperature in the mill does not exceed that reached without air drying by more than 5 deg. The method used to control the amount of heat to be added is to vary the amount of hot air applied so as to maintain a fairly constant temperature of the coal-air mixture leaving the mill.

The third point is the question of steam temperature. I am rather convinced that there is no reason why in the next installation we should not go to 800 or 825 deg. fahr., for the steam temperature leaving the superheaters, or for that matter why this higher temperature should not be generally used. This is the greatest opportunity for gain in economy, and at a relatively small expenditure, that is presented to the designer at the present time. With the present inter-deck superheaters we frequently get rather high temperatures with no serious effect on the superheater, and no apparent effect on the turbine. We have radiant-heat superheaters installed in the bridge walls in some of our stoker-fired furnaces at Westport, which have been in service for nearly five years, operating with metal temperatures up to 1100 deg. fahr. They are in series with convection superheaters at the top of the first and second passes of the boilers, and maintain a very uniform steam temperature over quite a range of rating. The radiant-heat superheaters are not fitted with any type of flooding device and the boilers are banked frequently for protracted periods. If these superheaters will stand this sort of punishment, I can see no reason why we should not approach the same condition at Gould Street, and I anticipate raising the steam temperature as soon as we have some of the other operating problems cleaned up.

**F. W. Quarles:** Mr. Morrow asked how many men we require. I believe they average about fourteen per shift. The use factor of the boilers at the present time has been governed considerably by some of the changes that have taken place in the plant to rectify certain conditions. I think that at this time we cannot draw any satisfactory conclusions as to the use factor. Mr. Morrow also asked about the maintenance of the automatic control. So far the maintenance of the automatic control has been comparatively small on standard equipment. Where we have used new schemes we have got into difficulties, but in the case of the combustion control which is composed of standard pieces of equipment, it has had a very large job to do, much larger than in the usual plant. That is, on the induced-draft and forced-draft fan controls there are four drums that must be operated by this control, and there has been occasional trouble with interlocks which have caused breakage of some chains and other parts, but with the improvement of the interlocks, and the strengthening of certain parts, maintenance of this control should be cut down materially.

There was a question raised by Mr. Thomas about banking.

I don't believe we have any figures that we could furnish at this time regarding the amount of coal required in banking. We don't have any easy means of measuring it at the present time. However, it requires, about once every four hours, the use of burners to bring the pressure back to normal, having allowed the pressure on the plant to reduce about 100 lb., the plant being shut down completely.

Mr. Schnure asked about the necessity of using the 53 points on the control of the induced-draft fans. We feel, in the case of this plant, that it is necessary to have a large number of points on the control of the forced and induced-draft fans because of the large range in speed that is required. In other words, in order to keep large fluctuations from occurring in the $CO_2$ value it is necessary to make small changes of air flow. Now in this case the adjustment is made by means of speed of the fans and very little by means of dampers. The only damper control is on the induced-draft fan and that damper control is of very little effect in the range where the motors are running. Most of its effectiveness is confined to the period when the boiler is running on natural draft.

The grounding of the neutral of the main generators is solid; there is no series reactor or resistance used.

# The Conowingo Hydroelectric Development
## on the Susquehanna River

BY ALEX. WILSON 3RD[1]
Associate, A. I. E. E.

***Synopsis.***—*The Philadelphia Electric Company, through its subsidiaries, has just completed construction of the Conowingo dam and powerhouse to develop the fall of the Susquehanna River from the tail-race of the Pennsylvania Water and Power Company's dam at Holtwood, Penna., to a point within four mi. of tidewater. This project ranks as one of the largest hydroelectric developments in the United States and is exceeded in size by the Niagara Falls development only. The speed of its construction, requiring less than two years from the start of construction operations to regular operation of the first units, is an outstanding achievement.*

*In an average year, 1,250,000 kw-hr. will be delivered in Philadelphia at 220,000 volts, from the initial installation of seven 54,000-hp. water-wheel units, (ultimately to be increased to 11 such units), resulting in a saving of more than 750,000 tons of coal annually. These water-wheels and generators, together with the 27-ft. diameter butterfly valves installed as head gates, are the largest from the standpoint of physical dimensions yet constructed.*

*The concrete dam of gravity type, 4630 ft. long, develops a normal head of 89 ft., and has created a lake 14 mi. long. The spillway section, 2385 ft. long, has been designed to pass a maximum flood of 880,000 cu. ft. per sec. and is surmounted by movable crest gates for maintaining a constant head-water level.*

*Relocation of 16 mi. of railroad together with many State and County roads and bridges was required in the acquisition of lands for the reservoir.*

*Unusual features of the design and construction of the dam and power station together with a general description of the entire project, are included in this article.*

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THE Conowingo Hydroelectric Development, with an initial installation of 378,000 hp. in seven main units ultimately to be increased to 594,000 hp. in eleven units, ranks as one of the largest hydroelectric projects in the United States, as shown by the following table giving installed capacity in other large plants.

| Plant | Owner | Installed hp. |
|---|---|---|
| Niagara Falls | Niagara Falls Power Company | 425,500 |
| Conowingo | The Susquehanna Power Company | 378,000* |
| Muscle Shoals | United States Government | 260,000* |
| Holtwood | Pennsylvania Water and Power Company | 158,000 |
| Keokuk | Mississippi River Power Company | 150,000 |

*Initial Installation.

In the average year, the initial Conowingo plant will deliver 1,250,000,000 kw-hr. to Philadelphia and interconnected districts, resulting in an annual saving in coal of more than 750,000 tons.

From the standpoint of speed of construction, Conowingo is an outstanding achievement in the history of projects of similar size. Construction work was started March 8th, 1926, under Federal License approved February 20th, 1926, and on March 1st, 1928, less than two years after starting construction, the first units were placed in regular operating service.

It is the purpose of this paper to outline the general features of the project and to describe particularly the design and construction of the dam and power house, and hydraulic equipment.

### THE SUSQUEHANNA RIVER

With the exception of the St. Lawrence, the Susquehanna River basin is the largest and most important on the Atlantic Coast. Its total area of 27,400 sq. mi. includes 47 per cent of the total area of the State of Pennsylvania, 13 per cent of the total area of the State of New York, and two per cent of the total area of the State of Maryland, and extends north almost to Utica, N. Y., and west beyond Altoona, Pa.

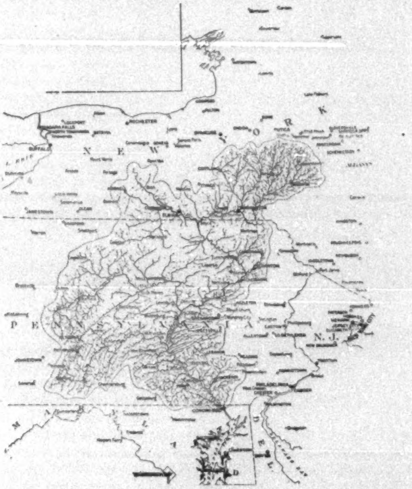

FIG. 1—MAP OF AREA DRAINED BY THE SUSQUEHANNA RIVER

The head waters of this river system are on the elevated plateau which separates the waters which flow south and east into the Atlantic streams from those flowing north and west into the Mississippi, St. Lawrence, and Great Lakes.

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[1] Construction Engineer, Philadelphia Electric Co., Philadelphia, Pa.

*Presented at the Regional Meeting of the A. I. E. E., District No. 2, Baltimore, Md., April 17-20, 1928.*

From Northumberland, situated at the junction of its east and west branches, the river has a fairly uniform grade of two and one-half ft. per mi., except for local rapids between the Muncy Dam and Conewago Falls, near York Haven. Below, or in the lower 40 mi. of its course, the slope increases to an average of five ft. per mi. to tidewater, and the width of the river becomes contracted, narrowing into a gorge which, in places, is reduced to a width of two-tenths to one-half mi. In the last 27 mi. of its run, the river drops from an elevation of 225 ft., with an average slope of 5.6 ft. per mi., causing a swift current which has worn a low water channel of great depth in many places.

Along this lower section, the river has cut its way through a range of table land, and its bed is walled by steep, rocky bluffs on both sides, affording excellent foundation for water-power developments. A portion of the fall in this section has been developed by the Pennsylvania Water and Power Company's dam at Holtwood, Pennsylvania. The Conowingo Dam will utilize the head from the Holtwood tail-race to within four mi. of tidewater.

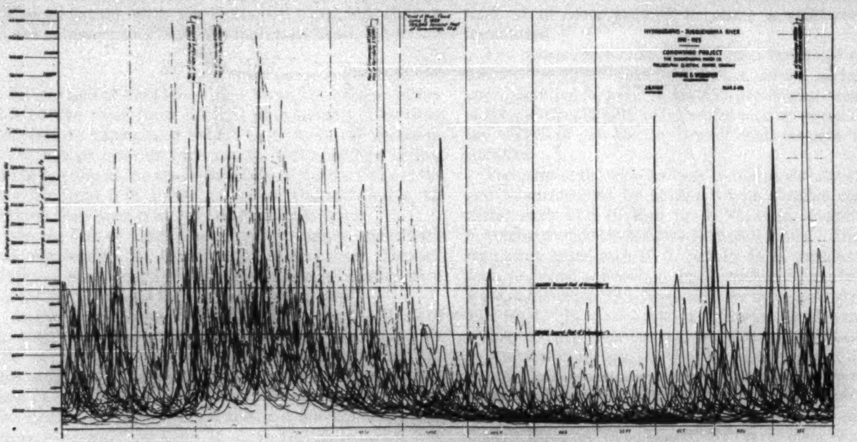

FIG. 2—HYDROGRAPHS—1891 TO 1925 INCLUSIVE

The annual precipitation over the area drained by this great river, according to records of the United States Weather Bureau, varies from 31.4 in. to 44.3 in., with a mean of 39.4 in.

The run-off, which eventually finds its way to the sea through the Susquehanna River, varies from 16.6 in. to 29.1 in. and averages 55 per cent of the rainfall. The run-off is at a minimum in August, September, and October, during which months it ranges from 5 per cent to 30 per cent of the rainfall and averages about 15 per cent. Reliable official records on the flow of the Susquehanna have been taken since 1891 at Harrisburg, which shows that, like all other Pennsylvania streams, its natural run-off varies widely both from day to day or week to week and from season to season.

High water frequently occurs in January from melted snow. Floods accompanied by ice gorges occur usually in March and result in a high water level, although with a lesser volume of flow than at times of clear water floods caused by heavy rainfalls, occurring over the whole or a portion of the water shed as late as June. In late summer or fall, periods of low water are frequently noted.

During the past century, there have been several great floods in this river, the most notable of which was that of June, 1889, which was coincident with, although not caused by, the Johnstown Flood, and which probably exceeded any flood that ever occurred in this stream. It is estimated that during this flood, the rate of flow reached a maximum of 730,000 cu. ft. per sec. A minimum discharge of 2200 cu. ft. per sec. was recorded at Harrisburg in 1909.

Due to the frequent recurrence of low-flow periods, which limit the amount of firm power available, large scale power development was not economically feasible until electric demand in nearby centers served from steam driven generating equipment, had become capable of absorbing the hydro power available during high-flow periods. This condition is met by the load of the Philadelphia Electric Company System and its interconnections with other utilities. Thus the Conowingo site, with a firm power value of but 30,000 kw., will initially deliver in Philadelphia 1,250,000,000 kw. hr. annually, resulting in an annual saving of more than

750,000 tons of coal and with the present shape of the daily load curve of the Philadelphia Electric Company System, the Conowingo plant can be relied on for a minimum peak capacity of 180,000 kw. which ultimately would otherwise have to be provided in steam plant capacity.

### CORPORATE ORGANIZATION

As the Philadelphia Electric Company will use practically the entire output of the Conowingo Development, it was necessary that it should control the operation of the plant. Its charter, however, does not permit it to operate or hold title to property in Maryland. These requirements were met by the organization of three subsidiary or otherwise controlled corporations, as follows:

The Susquehanna Power Company, incorporated in Maryland, to hold title to all the physical properties of the project located in that State, including the dam, power house and tail-race, and portions of the reservoir and transmission lines.

Philadelphia Electric Power Company, incorporated in Pennsylvania, to hold title to all physical property of the project located in Pennsylvania, this being principally lands for the reservoir and the greater portion of the transmission lines.

The Susquehanna Electric Company, which has leased for the term of the Federal License the properties of the Susquehanna Power Company in Maryland. This subsidiary under contract with the Philadelphia Electric Company operates the plant and sells the generated energy to the Philadelphia Electric Company. As set up, therefore, the Conowingo Hydroelectric Development has been made by and for the Philadelphia Electric Company, and is being operated as a part of that company's system.

### RELOCATION OF HIGHWAYS AND RAILROAD REQUIRED

The Conowingo Dam and Power House are located in Cecil and Harford Counties, Maryland, about six miles from the Mason and Dixon Line and four and one-half miles upstream from the town of Port Deposit. The reservoir above the dam has an area of 14 sq. mi. and extends above the dam a distance of 14.6 mi., of which 9.3 mi. are in the State of Pennsylvania. Relocation of 16 mi. of the Columbia and Port Deposit Branch of the Philadelphia, Baltimore, and Washington Railroad Company operating on the left bank together with numerous County and Township roads and one State road, including a steel-bridge crossing the river at Conowingo, Maryland, two mi. above the dam, were made necessary by the impounding of the waters in the reservoir.

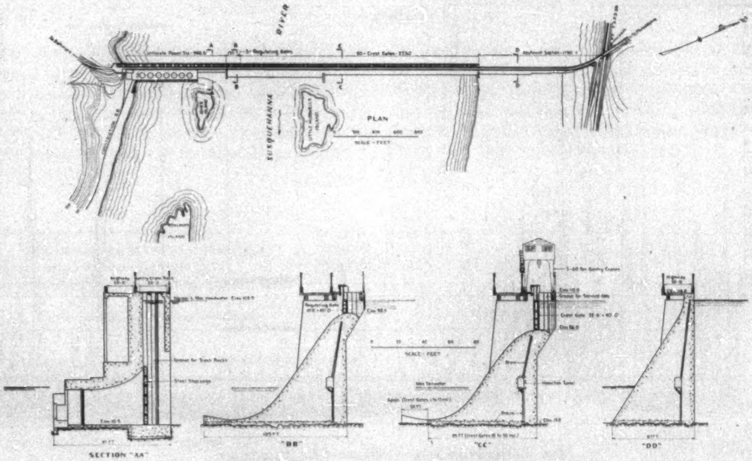

FIG. 3—GENERAL PLAN AND SECTIONS—CONOWINGO DAM

The total of these items involved a considerable amount of work. A new highway bridge with 20 ft. wide roadway, supported on the structure of the dam and power house has been provided together with 4.37 mi. of 18 ft. wide concrete highway connecting the new bridge with the existing State road on either side of the river. The relocation of the railroad on the left bank made necessary the construction of a double track road-bed from Port Deposit, Maryland, to Fishing Creek, Pennsylvania, and involved 1,460,000 cu. yd. of excavation (including borrow) 900 ft. of tunnel, 42,000 cu. yd. of concrete masonry in bridges and culverts and the laying of 20 mi. of single track.

### Maximum Pool Elevation

By agreement with the Pennsylvania Water and Power Company whose dam is located at Holtwood, Penna., upstream from the Conowingo Dam, a normal and maximum pool elevation, 108.5 ft. above sea level, has been adopted. At this elevation, the impounded waters of Conowingo Dam will be backed up over a portion of the Holtwood Plant's tail-race, which has not yet been excavated but which, if excavated, would result in increased head and power at the Holtwood plant. It was mutually agreed that this additional head could be developed more economically at Conowingo Dam, and arrangements were made, therefore, that the Conowingo pool should be maintained at the above elevation, with the Holtwood Company sharing in the gain accruing from the increased head.

### Site of Dam

At the site of the Conowingo Dam, the hills on either side of the river form natural abutments. The river bed and its banks, to a height well above the reservoir level, are of igneous formation. Core borings, drilled along the line of the up-stream face of the dam to depths varying from 5 ft. to 100 ft. below the rock ledge, all showed firm hard rock for their entire length.

On the left or Cecil County shore, ample space with rail connection to the Columbia and Port Deposit Railroad was available for the erection of construction camp and plant and for storage of materials.

As the main channel of the river ran along the Harford County shore, the power house has been located at this end of the dam. Space for construction plant at this side was somewhat limited by the rather abrupt rise of the river bank. To provide transportation facilities to the power house site, a single track railroad connecting with the Penn. R. R. in Havre de Grace was constructed on the tow-path of the old Tidewater Canal which formerly operated on this bank, but which has been abandoned since the latter part of the nineteenth century. A freight classification and material storage yard was established on Giles Island, located on the route of the construction railroad about three mi. below the dam.

### Design of Dam and Headworks

The dam is of solid concrete masonry construction, designed as a gravity section. Its total length, 4648 ft., includes the power house headworks, 950-ft. long and 2385 ft. of ogee type gate-controlled spillway section. To collect seepage water under the dam, and prevent excessive uplift, a longitudinal drain was installed on the foundation ten ft. six in. downstream from the face of the dam. Cross drains spaced 45 ft. on centers connect this drain to tail-water at the toe of the dam. Riser drains at all vertical construction joints connect the bottom drains to the inspection tunnel. To reduce seepage through the vertical construction joints, copper sealing strips were installed near the upstream face of the dam. Grout holes located two ft. inside the upstream face of the dam were drilled in the foundation to a depth of 20 ft., at 10-ft. intervals and grouted under 25 lb. pressure to form a cut-off wall against seepage through the foundations.

The dam and power house are founded on rock at an average elevation of about 12 ft. above sea level for the dam and 7 ft. for the power house. Due to folding and metamorphic intrusions, the rock surface presented, after removing all overburden and rock that could be barred loose and cleaning out all seams, was very rough and irregular and thus provided excellent bonding for the structures. Soft seamy rock was encountered in but two sections requiring more than removal of loose material to secure a satisfactory foundation.

The overhanging crest is an unusual feature of the spillway section. This permitted a curved surface, approximating the lower nappe of an overflowing stream of the depth of 22½ ft. to be formed without increasing the width of the section beyond that required for stability.

The crest of the main spillway is fixed at elevation 86 and is surmounted by 50 Stony type movable crest gates, each 22.5 ft. high by 41 ft. wide, operating in guides provided in concrete piers on the dam. Three regulating gates, each 10 ft. high by 41 ft. wide, have been provided adjacent to the power house on a fixed crest at elevation 98.5, for use in finer regulation of the pool level. In the design of the spillway, an allowance of 4000 lb. per linear foot was assumed for ice pressure at the water surface. A compressed air system, discharging air below the water surface upstream from the gates, has been provided to prevent formation of heavy ice against the gates. The above pressure was considered, therefore, to be concentrated at the piers. Electric heaters have also been provided to keep the gate guides free from ice. The gate piers, spaced 45 ft. on centers, continue up above the pool level, and support a runway at elevation 115, extending along the spillway section and power house headworks from which three electrically operated gantry traveling cranes operate the crest and regulating gates as well as the sectional head gates and trash racks on the power house. The gate piers also support the highway bridge, which has replaced the old Conowingo bridge, inundated in the reservoir.

The spillway section for the three regulating gates and 17 crest gates has been provided with a 20 ft. wide apron curving up from the toe of the dam to an angle of 12½ deg. with the horizontal in order to prevent erosion at the toe of the dam. Tests conducted at Worcester on a model of the spillway and apron indicated that the maximum erosion would take place about 150 ft. beyond the toe and might reach a depth of 25 or 30 ft.

below the river bed. These tests also indicated that practically no erosion would occur directly at the end of the apron.

The power house headworks section was designed as a gravity section to be stable, independent of the power house structure. The heavy bottom slab forming the floor of the intakes has been keyed into the foundations and the walls and roof of the intakes tied to this with heavy reinforcing to resist the uplift pressure on the intake roof. At the upstream face of the head works section, a reinforced concrete curtain wall extends to a depth of 40 ft. below the surface of the reservoir for the purpose of preventing ice and trash from entering the intakes below.

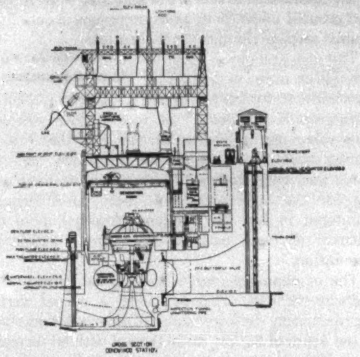
CROSS SECTION
CONOWINGO STATION

Fig. 4—Cross-Section of Power House

## POWER HOUSE STRUCTURE

The substructure of the power house, designed to meet the requirements of the water ways required by the hydraulic units and to support the superimposed loads of the water-wheels and power house superstructure, was constructed of reinforced concrete. A maximum depth of foundation excavations to elevation minus 20.5 ft. was required at the hydraucone draft tubes of the wheels. Where spreading type, draft tubes were used on three of the units, excavation was carried to elevation 16.5 ft. below sea level. Weep-holes were provided in the floors of the draft tubes to relieve excessive uplift pressures. At the downstream face of the substructure, the supporting piers have been extended to provide guides for draft tube stop logs.

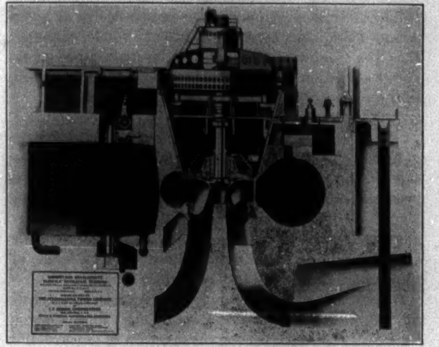

Fig. 5—Section Through Water Wheel Unit

Upstream from the units and below the level of the scroll cases, is an inspection tunnel from which access is afforded to each draft tube and to the butterfly valve thrust bearings and the valve in the unwatering system. Seepage through construction joints in the

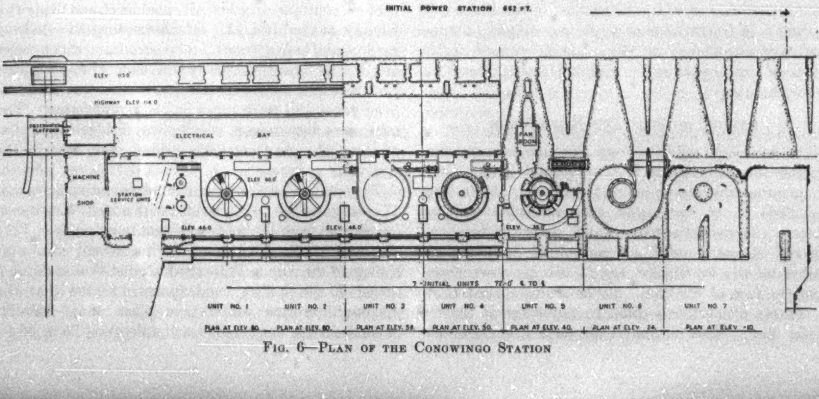
INITIAL POWER STATION 652 FT.
ELEV 150
HIGHWAY ELEV 114.0
OBSERVATION PLATFORM
ELECTRICAL BAY
MACHINE SHOP
STATION SERVICE UNITS
ELEV 60.0
ELEV 48.0
ELEV. 48.0
FAN ROOM
ELEV 36.0
7-INITIAL UNITS 72'-0 ℄ TO ℄
UNIT NO. 1
UNIT NO. 2
UNIT NO. 3
UNIT NO. 4
UNIT NO. 5
UNIT NO. 6
UNIT NO. 7
PLAN AT ELEV. 80.
PLAN AT ELEV. 80.
PLAN AT ELEV. 58
PLAN AT ELEV. 50.
PLAN AT ELEV. 40.
PLAN AT ELEV. 24.
PLAN AT ELEV. -10.

Fig. 6—Plan of the Conowingo Station

substructure and head works is collected in a trench running in the inspection tunnel and drained to a sump at the west end of the power station, where two small pumps are provided. Below this tunnel is a 42-in. cast iron unwatering header draining to a drainage pump of large capacity located at the shore end of the station served by two 15,000-gal. per min. pumps. Each draft tube, scroll case, and intake upstream from the butterfly valve is connected to this unwatering header through suitable valve control piping so that this central pumping installation can be used to unwater any one unit if desired. The main power station superstructure of the initial installation includes the generator room, which is about 70 ft. wide by 75 ft. high by 650 ft. long. The electrical bay between the generator room and headworks is a two story building containing the 13,800-volt bus and switch compartments. Compartments for step-up transformers are located on the roof of the electrical bay, together with the main control room and the station service control room from which windows afford a direct view of the generator room. The 220-kv. switching station is located on the roof of the generator room. The frame of the power house superstructure is designed of reinforced concrete on a structural steel frame with reinforced concrete roof carried on steel trusses. All loads imposed by the switching station on the roof are carried down to the substructure through the steel columns heavily reinforced with concrete. The loads of the two 150-ton cranes are carried on separate steel columns which are tied in with the building columns for the lateral support only. A dismantling area designed for uniform load at 2000 lb. per sq. ft. has been provided at the shore end of the power station for the purpose of assembling such large parts as the generator rotors and water-wheel runners. A standard gage railroad enters the building at this point and also affords ready means of delivering material to the machine shop located beyond the generator room. An office bay has been constructed between the power house and shore and is equipped with an elevator operating between elevation 35 and the reception room, at the elevation of the highway bridge.

## Hydraulic Equipment

Initial installation provides for seven 54,000-hp. Francis runner, vertical-shaft water-wheels, operating under normal head of 89 ft. and at 81.8 rev. per min. each direct connected to a 40,000-kv-a., three-phase, 60-cycle, 13,800-volt generator. These water-wheels, generators, and valves are the largest in physical dimensions constructed to date.

There are also two 1900-hp. station service units.

The shape of the intake was determined largely by the use of butterfly valves as head gates for the water-wheels, permitting the intakes to be designed with a wide entrance near the bottom of the river and low entrance velocity, which is accelerated uniformly to a maximum in the scroll case. The intake of each main unit is divided into two sections by a vertical reinforced concrete wall which extends to within 22½ ft. of the center line of the butterfly valve. Guides for steel head gates and sectional trash racks have been provided at the entrance, together with guides for a mechanical trash rake which operates on rails on the headworks. Head gates and trash racks are operated by the same gantry cranes described for the crest gates.

Seven water-wheels are connected to generators of different manufacture. All water-wheel runners have been designed with the same clearance dimensions and the same number of speed-ring vanes and guide vanes. The waterways have the same general dimensions and the valve control mechanism and various auxiliaries are alike. As the runners of the different manufactures are interchangeable, only one spare runner is required. Four water-wheels have draft tubes of the hydraucone type. Spreading draft tubes have been constructed for the other three water-wheels. The governors are of the actuator type with flyballs driven through gearing from the main shaft and are operated by oil pressure cylinders. There is one oil pressure system for each pair of units. An oil storage and purification system has been provided for all of the governors and bearing oil of all units, including station service units. With each main water-wheel unit, a 27-ft. diameter vertical shaft, butterfly valve, complete with operating equipment, oil pressure system, and accessories, has been installed at the water passages to the runners. These valves have a cast steel housing and a wicket of cast steel, a forged steel shaft and a plate steel penstock liner, extended 12 ft. upstream in the intake passage. These valves are operated by oil pressure from a central oil pressure system. All butterfly valves and the plate steel scroll cases to which they are attached have been furnished by the same manufacturers as the

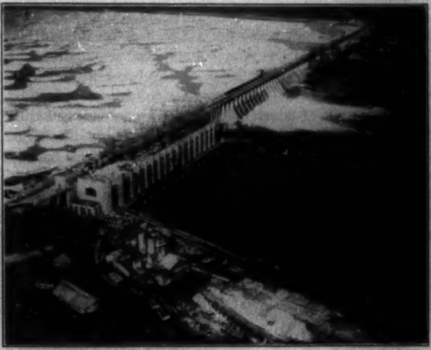

Fig. 7—Aerial View of Completed Dam and Power House, Taken February 1927

respective water-wheels units on which they have been installed. The weight of the rotating elements, together with hydraulic thrust, is carried by the thrust bearings on top of the generators. These bearings are supported by bracket arms extending radially from the structural steel pit liner, which also supports the stator of the generator. Both spring-type thrust bearings and Kingsbury thrust bearings have been used.

### RIVER DIVERSION AND CONSTRUCTION METHODS

At the beginning of the work, a progress schedule was carefully worked out to determine the progress necessary to be made by the various operations of the work to coordinate these operations with the scheme of river diversion. This schedule contemplated operation of the first two units on June 1st, 1928. Construction progress, however, was considerably better than scheduled with the result that two units started commercial operation on March 1st, and a third unit, a few days later.

In the low-water season of 1926, a cofferdam of the puddle-chamber type was constructed enclosing the power house and west branch of the tail-race, an area of about 14 acres. The top of this cofferdam was built to elevation 42, at which elevation it was estimated that it would not be topped by flood of any volume less than 350,000 cu. ft. per sec. so that work on the heavy excavation of the power house foundations and draft tubes could reasonably be expected to proceed without interruption by floods in the Spring of 1927. Simultaneously with the construction of the power house cofferdam, another cofferdam of the spaced crib type was constructed from the Cecil County shore, extending to within approximately 700 ft. of the power house cofferdam. About the middle of November, a flood of 350,000 sec. ft., the greatest November flood that has been recorded for the Susquehanna River occurred. The head water elevation rose to within a few inches of the top of the sand bags which had been placed on the power house cofferdam and, of course, topped the spaced crib cofferdam on the other side of the river. As the foundations for the dam had been completed in this area with alternate spillway sections each including two bridge piers poured to a height above the river level, it was not necessary to unwater this cofferdam again after the flood has subsided.

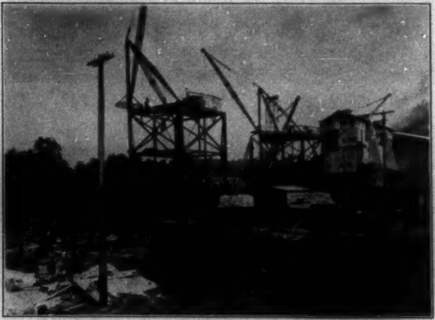
FIG. 8—CONSTRUCTION PLANT—EAST SIDE OF RIVER

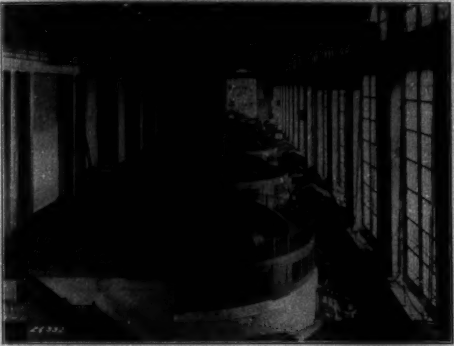
FIG. 9—GENERATOR ROOM—CONOWINGO STATION

During the winter and early spring of 1927, the pouring of the pier sections was completed up to and including the highway bridge, leaving intermediate sections 38 ft. wide at the level of the foundation (elevation 22) to provide for the diversion of the river during the summer of 1927. Likewise the power station headworks was completed during this period up to an elevation well above flood levels.

As soon as the spring floods of 1927 had sufficiently subsided, the cofferdam was extended from the last completed spillway section to the power house headworks, and by September, the foundations of the dam had been completed in this last cofferdam and the alternate sections poured above the elevation of the top of the cofferdam. With the removal of this cofferdam, twenty 38 ft. wide notches in the spillway, together with eight 10 ft. high by 18 ft. wide sluices through the spillway, were taking care of the river flow.

Final closure of the notches was commenced early in October, 1927. The easterly ten notches were first brought up to elevation 30, and the west ten to elevation 35. These two groups, with a 5-ft. difference in bottom grades, were then raised alternately in 10-ft. lifts, thus providing 5-ft. flow through ten openings in addition to the flow through the eight sluices. In the actual closing of the water-way at each 38-ft. opening, a steel and timber flap gate hinged at the top from the adjoining spillway sections was used. The gantry cranes provided for the crest gates were used to handle these flap gates. With the raising of the notches and corresponding rise of the headwater level, the discharge capacity of the eight sluices increased so that finally, when the notches had been raised to about elevation 50, the discharge from the sluices was equal to the river flow and the closing of the notches was completed without the use of the flap gates.

After the concrete in the notches had been completed to crest elevation, final closure of the eight sluices was made by lowering specially designed, reinforced concrete gates, weighing 75 tons each, and then filling the sluiceway opening with concrete.

Closure of the notches was hampered through November and December, 1927, by high water. Favorable flow conditions occurred in January, however, permitting completion to crest elevation on January 16 and on January 17, 1928, the sluiceway gates were dropped, making the final closure of the dam.

For the construction of the dam, a steel work trestle with deck at elevation 60 was built on the toe of the dam. Three self-propelled, electrically-operated gantry travelers, each equipped with a 15-ton steel derrick and concrete elevator, were used, the travelers operating on rails at the sides of the trestle deck and being designed to allow clearance for cars operating on the three standard-gage tracks, also provided on the trestle deck. The concrete mixing plant for the dam consisted of four mixers of 2-cu. yd. capacity each, and was so designed that the mixers discharged directly into hoppers mounted on cars on the work trestle. Gasoline locomotives were used to transport the concrete from the mixing plant.

In the construction of the power house and headworks, a central concrete mixing plant consisting of two mixers of two cu. yd. capacity each, was used. Placing of concrete was accomplished with 16-in. chutes from wood towers 250 ft. high. Guy derricks were used in handling forms and other materials. Erection of structural steel was accomplished by use of a traveling derrick mounted on the headworks. This traveler was also used to erect the steel arbor structure of the 220-kv. switching station on the roof of the generator room.

The following quantities involved in the construction of the dam and power house will be of interest:

| | |
|---|---|
| Cofferdam Cribs | 4,250,000 cu. ft. |
| Rock excavation, including tail-race | 348,000 cu. yd. |
| Forms | 3,850,000 sq. ft. |
| Concrete | 660,000 cu. yd. |
| Structural steel | 9,500 tons |
| Reinforcing steel | 6,400 tons |
| Hydraulic machinery | 6,500 tons |

A maximum working force of 5300 men was employed on the project.

The design and construction of the dam and power station, including installation of hydraulic machinery and 13,800-volt electrical equipment, the relocation of the tracks of the Columbia and Port Deposit Railroad, and the design and construction of the 220-kv. switching station on roof of generator room and the transmission lines, were awarded to outside contractors. Acquisition of all lands required by the project and all negotiations with Federal, State, and County Commissions were conducted by the Power Companies direct. All matters of design and construction were also under the general supervision of the Power Companies.

## Discussion

For discussion of this paper see page 906.

# Electrical Features of the Conowingo Generating Station and the Receiving Substations at Philadelphia

BY R. A. HENTZ[1]

Member, A. I. E. E.

***Synopsis.**—The paper outlines the principal electrical features of the Conowingo development. This includes a description of the main units and their connections, and an outline of the station auxiliary supply and the 220,000-volt substation which it was necessary to build on the roof of the power plant.*

*A description is included of the 220,000-volt substation at Plymouth Meeting, the Philadelphia terminus of the Conowingo lines, as well as the lines of the Pennsylvania-New Jersey Interconnection. At this substation are located the 30,000-kv-a. synchronous condensers installed for stability purposes, as well as a 66-kv. installation. Three winding 220/69/13.3-kv. self-cooled transformer banks of 130,000-kv-a. rating, arranged for tap changing under load, are installed here.*

*A description is also included of the Westmoreland Substation where the 66-kv. lines from Plymouth Meeting tie in with the 66-kv. "backbone" of the Philadelphia Electric System. At this substation, 30,000-kv-a. synchronous condensers for power-factor correction are located, as is also an extensive 13,200-volt installation for controlling transmission lines to various distribution substations.*

* * * * *

THREE stations or substations are involved in delivering the electrical energy from the Conowingo development into Philadelphia:

a. The Conowingo Hydroelectric Generating Station.

b. The 220/66-kv. step-down substation at Plymouth Meeting just outside Philadelphia.

c. The combined 66-kv. switching station and 66/13.2-kv. substation in Philadelphia (the Westmoreland Substation) where tie in with the existing system of the Philadelphia Electric Company is effected.

These, together with the steam generating stations and high-voltage substations of the Philadelphia Electric System are shown in Fig. 1.

## CONOWINGO GENERATING STATION

The ultimate development provides for eleven 40,000-kv-a. generators and three 220-kv. transmission lines, of which seven generators and two lines are being installed initially.

*13.8-Kv. and 220-Kv. Layout.* Fig. 2 is the main one-line diagram, the initial installation shown solid, the future dotted.

The 40,000-kv-a. main units generate energy at 13,800 volts and step up to 220,000 volts through 80,000-kv-a. transformers. It is planned to operate the plant as a whole in parallel on the 220-kv. bus, but to reduce the cost of transformers and 220-kv. switching equipment, two generators are tied together and to a transformer bank, thus forming an 80,000-kv-a. group. Thus ultimately, if such operation is satisfactory, there will be six such groups paralleled only on the 220-kv. side, except that the last one (generator No. 11 and transformer No. 6) will be necessarily of but 40,000-kv-a. capacity.

Should it at some future time be deemed desirable for any reason to operate in parallel on the 13.8-kv. side, then by means of additional construction the various buses of this voltage may be tied together, some through reactors, to form either a four-section ring bus or a three-section straight bus. The reactors may be cut out by means of a disconnecting switch (operated only when no current is flowing through the reactor). Initially the No. 3-No. 4 and the No. 5-No. 6 sections are tied together by an oil circuit breaker, thus providing greater flexibility of operation between these four generators. It will be noted that generators Nos. 3, 6, and 9 and transformer banks Nos. 2, 3, and 5 may be double-bussed in the future should the 13.8-kv. ring be formed. This is to permit testing a 220-kv. line from a generator (about one-half the capacity of which is required for such test) with the least interference to the maximum output over the remaining line or lines.

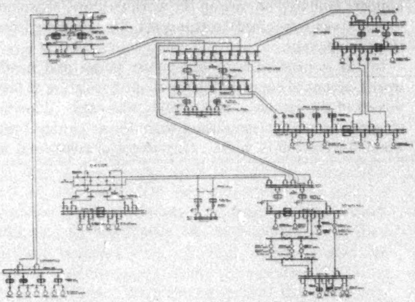

FIG. 1—MAJOR CONNECTIONS OF THE PHILADELPHIA ELECTRIC CO. SYSTEM

There will be two feeders, each connected to separate sections of the 13,800-volt bus to supply a transformer bank used for station service, and provision is made for two other feeders for the future supply to communities in the vicinity.

Two plans for the 220-kv. structure were considered;

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[1] Engineer, Station Electrical Division, Philadelphia Electric Co., Philadelphia, Pa.

*Presented at the Regional Meeting of the A. I. E. E., District No. 2, Baltimore, Md., April 17-20, 1928.*

one a complete double bus layout which due to the characteristics of the site would have to have been located on the west shore some distance from the power house with consequent high cost and operating inconveniences due to distance from the operating room; the other the most flexibly operated bus that could be located on the roof of the power house, which location would be considerably cheaper and more conveniently operated than the first. This latter was decided upon, as it was possible to develop quite a flexible layout within the space limitations and to incorporate two features, inherent in a double bus layout, that were felt to be essential. These were reserve oil circuit breakers for the lines, and immunity from protracted shut-down due to failure of a part of the bus. On account of their more frequent tripping and the speed with which lines can be restored to service, as well as the greater capacity involved, reserve breakers for the lines were considered essential, whereas one oil circuit breaker was felt to be sufficient for a transformer bank.

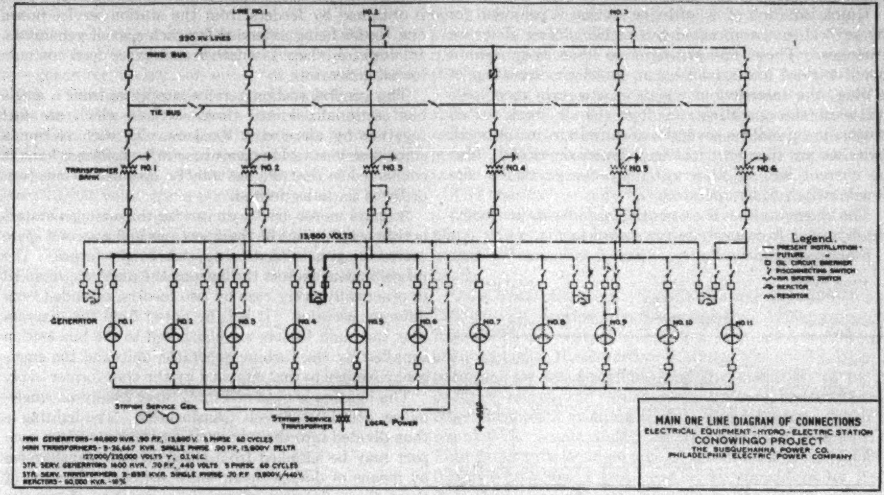
LINE NO. 1
NO. 2
NO. 3
220 KV LINES
RING BUS
TIE BUS
TRANSFORMER BANK
NO. 1
NO. 2
NO. 3
NO. 4
NO. 5
NO. 6
13,800 VOLTS
GENERATOR
NO. 1
NO. 2
NO. 3
NO. 4
NO. 5
NO. 6
NO. 7
NO. 8
NO. 9
NO. 10
NO. 11
STATION SERVICE GEN.
STATION SERVICE TRANSFORMER
LOCAL POWER
MAIN GENERATORS - 40,000 KVA. .90 P.F., 13,800 V. 3 PHASE 60 CYCLES
MAIN TRANSFORMERS - 3-26,667 KVA. SINGLE PHASE .90 P.F., 13,800 V DELTA 127,000/220,000 VOLTS Y, O.I.W.C.
STA. SERV. GENERATORS 1600 KVA. .70 P.F., 440 VOLTS 3 PHASE 60 CYCLES
STA. SERV. TRANSFORMERS 3-833 KVA. SINGLE PHASE .70 P.F. 13,800 V/440 V.
REACTORS - 60,000 KVA. -10%
Legend.
PRESENT INSTALLATION
FUTURE
OIL CIRCUIT BREAKER
DISCONNECTING SWITCH
AIR BREAK SWITCH
REACTOR
RESISTOR
MAIN ONE LINE DIAGRAM OF CONNECTIONS
ELECTRICAL EQUIPMENT - HYDRO - ELECTRIC STATION
CONOWINGO PROJECT
THE SUSQUEHANNA POWER CO.
PHILADELPHIA ELECTRIC POWER COMPANY

Fig. 2—Single-Line Diagram of the Conowingo Power Station

Fig. 3—General View of the 220,000-Volt Installation on the Roof

To the left, 2,500,000-kv-a. oil circuit breakers; to the right, 220-kv. lightning arresters.

The reserve line oil circuit breakers are located at the ends of the 220-kv. structure and connect the main tie bus with the ring bus. They are provided

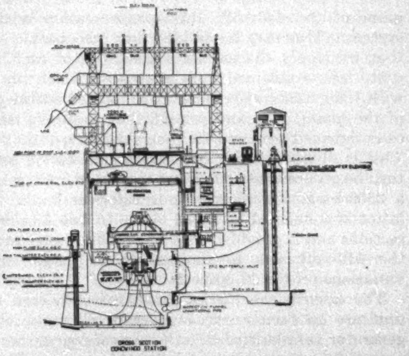
CROSS SECTION CONOWINGO STATION

Fig. 4—Conowingo Power Station Cross-Section

with the same relay equipment as the regular line breakers, and by opening the latter and closing the ring-bus-line air-break switch, (which is motor-operated and interlocked in the same manner as the bus sectionalizing switches), the reserve breaker is electrically substituted for the regular one. Fig. 3 is a general view of the 220-kv. oil circuit breakers.

Quick isolation of a defective section is provided for by several motor-operated bus sectionalizing air-break switches. These are arranged so that they cannot open or close under load by an interlock consisting of a plug, the insertion of which in a certain receptacle will close the operating circuit of the air-break switch motor, provided the several associated air- or oil-break switches are in such a position (open or closed) that no current will be interrupted by the particular air-break switch to be operated.

The above outlines the essential features of the electrical layout. A cross-section is shown in Fig. 4.

*Station Auxiliary System.* Fig. 5 is a one-line diagram of the 440-volt, three-phase station auxiliary system. This may be divided into two parts: first, that to supply the essential auxiliaries of each main unit (this is obtained from alternators which together with their exciters are directly connected on the shaft of the main unit); and second, that to supply the less essential auxiliaries and the general lighting of the plant. This is obtained from two 1600-kv-a. station service turbine generators (with direct-connected exciters), and a 2500-kv-a. station service transformer bank. This latter is connected as noted above to two 13,800-volt sections and is provided with an induction regulator on the 440-volt side to compensate for large voltage variations on the 13,800-volt side.

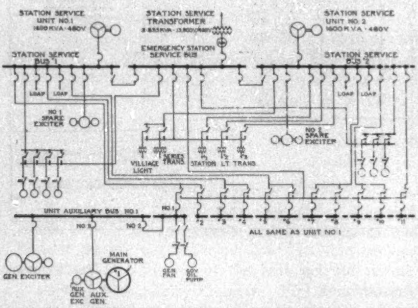

FIG. 5—440-VOLT STATION SERVICE AT CONOWINGO

The essential auxiliaries associated with each main unit are an exciter set, a governor oil pump, and a generator ventilating fan. Of these of course the most essential is the exciter and for this reason the unit auxiliary bus is divided into two parts tied together through a circuit breaker, so that the generator fan and governor oil pump may be disconnected, allowing the shaft-end auxiliary generator to continue driving the motor-generator set. The governor oil pumps for each pair of units are each capable of supplying the governors of both main units and both are running all the time. The generator fan is not needed when the air is being discharged into the turbine hall.

Emergency supply to all of these essential auxiliaries is obtained by feeders from the station service buses, one feeder being extended for each pair of generators. In addition there is another emergency feed common for all generators.

The general station service supply is from a single bus sectionalized into three sections which are tied together by air circuit breakers. To each section a station service turbine generator or transformer bank is connected so that the bus may be operated in one, two, or three parts as desired.

A spare motor-driven exciter for the main generators is connected to one of these sections and a second spare exciter may be added to another in the future. The miscellaneous motors throughout the plant are supplied in practically every case by two feeders, extended from different sections. It will be noted from the diagram that the main feeders are connected to the bus section supplied by the turbine generator units and the emergency feeders to that supplied by the transformer bank.

The lighting is obtained from three 200-kv-a., single-phase, 440/110-220-volt transformers. The lighting is thus divided into three independent parts, though each part may be supplied from either of two transformers by means of double-throw knife switches. In each of these three lighting groups is a number of circuits which will be thrown over automatically to one of the two control storage batteries in the event of failure of the regular a-c. supply. Two 20-kv-a. series lighting transformers are installed for lighting the highway over the dam. A bank of transformers stepping up to 2300 volts, three-phase, is used to supply service to the operating village nearby. Air circuit breakers are used throughout on the 440-volt auxiliary system.

*Excitation System.* As noted above, each of the main generators is excited from individual motor-generator exciter sets. These consist of a 375-hp. induction motor, a 240-kw., 250-volt main exciter, and a 10-kw., 250-volt pilot exciter operating at 1200 rev. per min. Consideration was given to having these exciters mounted on the same shaft with the main unit, but due to their capacity and the slow speed (81.8 rev. per min.) a very expensive exciter of quite large dimensions and of slow response would have resulted if indeed they could have been satisfactorily built. As high-speed excitation was essential for stability of operation, it was necessary to use motor-generator exciters.

This high-speed excitation has been described in the technical press.[2] The regulator is a combination of rheostatic and vibrating contact types, the general principle being that for sudden changes of load the contacts raise or lower the voltage very quickly and the face plate rotates to a new position after which the contacts cease vibrating. This combines the advantages of the two types, obtaining the quick response of the one and the reduced contact maintenance of the other.

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[2] "Quick Response Excitation for Alternating-Current Synchronous Machines," C. A. Powel, *Electric Journal*, April 1927, p. 157.

Circuit breakers are installed so that excitation for each unit may be obtained either from the regular motor-generator exciter, or either of the two spare exciters. Emergency excitation for the auxiliary generators and the station service generators may be obtained from the spare exciters in the same manner.

*Main Generators.* The main generators are of unusual size, rated 40,000 kv-a., 36,000 kw., 90 per cent power factor, 13,800 volts, three-phase, 60 cycles. Though there are others of larger kw. capacity, yet on account of their slow speed, these are physically the largest ever built. They are provided with 88-poles and operate at 81.8 rev. per min. Mounted on the same shaft and above the thrust bearing is a 715-kv-a., 500-kw., 70 per cent power factor, 440-volt, three-phase, 60-cycle generator and its 41-kw. 250-volt exciter. Four of the units are provided with spring type thrust bearings and the other three, with Kingsbury thrust bearings. The designs of the two manufacturers who built the generators have been so worked out that the units have the same general dimensions, which adds greatly to the appearance of the generator room. The neutrals of both the main and auxiliary generators are brought out for differential relay protection and in the case of the main generators are then grounded through a 4-ohm resistor which is common to all of the units, even though groups of these generators are separated from one another on the 13,800 volt side. The neutrals of the auxiliary generators are ungrounded. Fifteen temperature resistors are provided in the main machines and operate recording temperature indicators. The generators are roughly 38-ft. in diameter, 32-ft. high, and weigh, together with the thrust bearing, auxiliary unit and its exciter, well over 500 tons on the average. See Fig. 6. The weight on the thrust bearing including water thrust is 1,200,000 lb.

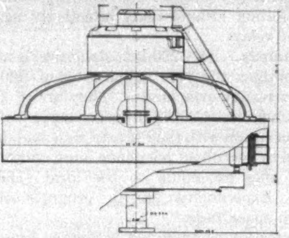

FIG. 6—40,000 KV-A. GENERATOR

*Main Transformer Banks.* Each main transformer bank is of 80,000-kv-a. capacity, consisting of three 26,667-kv-a. units, Y-connected on the 220-kv. side, with solidly and permanently grounded neutrals, and delta on the 13.8-kv. side. Four of these banks are being installed initially together with a spare single-phase unit, making thirteen transformers in all. They are provided with one seven and one-half per cent tap in the high-tension winding and are insulated for 187 kv.

The units are water-cooled and normally receive their water supply directly from the lake formed by the dam, the water flowing through the cooling coils by gravity. When reduced pond level makes it necessary, motor driven pumps supply the cooling water.

The transformer may be run on its own wheels on to a transfer car which carries it to the west end of the plant, where a crane lowers it to the same level as the generator room into which it is run over the yard tracks.

*Oil Circuit Breakers.* The oil circuit breakers for 220,000-volt service are rated 187-kv., 1000-ampere, 2,500,000 kv-a. rupturing capacity. Potential networks are attached to the condenser bushings which will supply potential for synchronizing and the operation of impedance relays and instruments. These breakers in their permanent position rest on two I-beams. Their removal is accomplished in the following manner: Four jacks raise a single pole of the breaker a sufficient distance to allow a small car to be slipped under it; it is then lowered until it rests on this car in which position it just clears the I-beams. This small car with the breaker is then moved on to a larger car which is then moved to the west end of the station, where the smaller car carries the breaker under a crane which lifts it down into a bay similar to those in which the main transformers are located. From here it is taken into the plant in the same manner as the transformers.

The 13.8-kv. breakers are rated 15 kv., but are insulated for 25 kv. as are also all the insulators and current transformers. The generators and light and power breakers are of 2000 ampere capacity, the bus tie of 4000 ampere capacity. They are motor-operated, and have a rupturing capacity of 1,500,000 kv-a. The section of the station in which they are located is divided into a number of smokeproof compartments so that fire and the resulting soot will be confined to a comparatively small area.

*Relays.* The main generators have percentage differential relays *P Q Y*-28, which take care of phase-to-ground and phase-to-phase faults. No provision is made for short circuits between two sections of the same winding or between turns of each section. Overvoltage *C V* and mechanical overspeed relays with their contacts in parallel protect against excessive frequency and voltage that may occur upon sudden loss of load.

The unit auxiliary and station service generators have single winding differential relays *P Q* and in addition the station service ones have overload *C O A* protection.

The main transformers are equipped with two-winding differential relays *P Q*-21 and low energy ground relays *C O* on the low-voltage side. In addition overload relays *C O A* provide protection against a 220-kv. bus failure between phases and act as back-up relays for the phase-to-phase relays on the 220-kv. lines.

The station service transformer bank is protected by differential *P Q*-21 and overload *C O A* relays. Since the two 13.8-kv. sections which supply this bank would be left together if both the two breakers that control it were left closed at the same time, a long time auxiliary relay operates an alarm, thus warning the operator of this condition.

The 13.8-kv. bus sections are protected by differential *P Q Y*-28 and low energy ground *C O* relays. The two bus sections which may be tied together require a slightly amplified scheme over that required for the two that are entirely isolated.

The 220-kv. line breakers and the 220-kv. bus tie breaker (which as pointed out above may be substituted electrically for them) are each provided with:

a. Three low setting directional impedance *C Z* relays to provide phase-to-phase protection. Due to the fact that the maximum line current is so great and the range of connected generating capacity so large, it is possible to have phase faults with minimum generating capacity involving less than half maximum full load current. In order to properly clear under minimum generating capacity conditions and to prevent the maximum full load current from tripping the lines

b. Three instantaneous undervoltage *S V* relays.

c. Three instantaneous over-current *S C* relays are provided whose contacts are in parallel. The operation of either of these in turn operates

d. One auxiliary *M C* relay whose contacts normally short circuit the current coils of the impedance relays *a*. In case of fault occurring with minimum generating capacity, the voltage relay *b* operates allowing the impedance relay *a* to function; in case of fault occurring with maximum generating capacity the current relay *c* operates allowing the impedance relay *a* to function. Thus, heavy load currents will not cause relay operation unless of such high value as to operate relay *c* which is set well above maximum full load.

Entirely separate from the relays described above are those installed for phase-to-ground protection. These are

e. One inverse time directional *C W C* relay, the upper pole winding of which is connected in the residual circuit of the 220-kv. line current transformers while the lower pole winding is connected in series with the lower pole windings of other similar relays to a current transformer in the 220-kv. station ground. While this relay is entirely selective, there is also installed for the more rapid disconnection of heavy current faults

f. One plunger type instantaneous over-current *S C* relay connected in the residual circuit of the line-current transformers. This relay is made directional by

g. One instantaneous directional *C W C* relay whose contacts are in series with *f*.

There is no back-up phase-to-phase protection to the 220-kv. lines, unless the overload relays on the transformers noted above were so considered, which of course clear the supply to the 220-kv. bus. However, it is expected that phase-to-phase faults will be extremely rare. Phase-to-ground back-up protection is provided by the use of

h. One low energy ground *C O* relay set higher than the main relay and connected in the residual of a second set of line-current transformers (on the other bushings of the oil circuit breakers) used for instruments. Its functioning operates a second trip coil. Thus this back-up relay comes into play should the regular trip coil fail. Also it operates first on faults involving small currents.

It is to be noted that the transformer overload relays are set selectively against the line impedance relays and transformer ground relay selectively against the line ground relays.

*Miscellaneous.* The 220-kv. structure is unique in that it contains the first installation of 220,000-volt lightning arresters ever made. They are of the oxide film type and consist of 666 disks per leg.

Communication with the Philadelphia load dispatcher is provided by two direct telephone lines, and in addition there are lines extending to the local (Darlington) exchange. Experiments are in progress using short wavelength space radio.

Fire protection is provided by water lines, carbon tetrachloride extinguishers, and a portable Foamite generator. In addition there are two stationary Foamite generators which can be connected to a system of piping for fighting fires in the main step-up transformer banks. Ordinarily this header is disconnected from the piping in the transformer bays but can be quickly connected by means of flexible hose. Water will be used to fight generator fires, easily connected links of hose being used to make the necessary connections.

The operating room is located at about the middle of the ultimate station and is provided with a pipe room beneath. Special consideration was given to lighting (both day and night) in order to avoid glare on the instruments. A skylight with a diffusing sash beneath is used.

Installed in the operating room are three semicircular switchboards arranged one behind the other. The first is a bench board, on which are mounted control switches and indicating lamps for the control of main and direct-connected auxiliary generators, step-up transformers, and 220-kv. oil circuit breakers and air-break switches. Back of the bench board is an instrument board on which are mounted the ammeters, voltmeters, wattmeters, reactive kv-a. indicators, etc., for the main circuits. Careful study was given to the location of equipment on the bench board and instrument board in order to facilitate accurate and easy operation. Back to back with the instrument board is a relay board on which are mounted the main protective relays. Around the rear and side walls of the room are located other boards for the control of the house service generators and transformers and for the voltage regulating equipment on the main and auxiliary generators.

250-volt control and emergency lighting is supplied from two 632-ampere hr. storage batteries and three 15-kw. motor-generator sets.

In line with the company's standard practise, telephone drop signals are used to indicate any occurrence that should be brought to the operator's attention.

Oil handling is accomplished by means of two 500-gal. per min. pumps located in the basement and five 12,000-gallon tanks located underground just outside the plant, together with an extensive system of piping. This consists of supply and discharge lines extended directly to the transformers and 220-kv. breakers, and conveniently near the 13.8-kv. breakers.

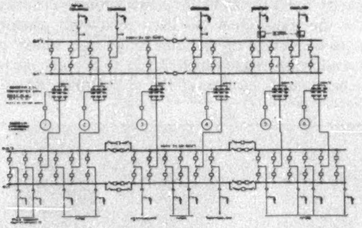

FIG. 7—SINGLE LINE DIAGRAM OF PLYMOUTH MEETING SUBSTATION

## PLYMOUTH MEETING SUBSTATION

The location of this substation about ten mi. northwest of the Westmoreland Substation was determined not only by the fact that it would be the terminus of the 220-kv. lines from Conowingo, but also for those of the interconnection with the Pennsylvania Power & Light and Public Service Electric & Gas Companies. The particular site chosen was directly alongside a heavy freight line (the Trenton Cut-Off) of the Pennsylvania Railroad, as this provided the necessary facilities for handling the very heavy apparatus involved in a substation of this character.

The function of the station is to step-down the energy received over the above 220-kv. lines to 66 kv., the existing high capacity transmission voltage of the Philadelphia Electric System, and to provide for synchronous condensers used mainly for stability purposes. Fig. 7 is a single-line diagram of this substation which may be considered in three parts, first, the 220-kv. substation with the step-down transformers, second, the 66-kv. substation, and third, the building housing the synchronous condensers and operating room. Figs. 8 and 9 show the plan and cross-section of it and Fig. 10 gives an artist's conception of how the completed substation will look. The area of land purchased is 40 acres.

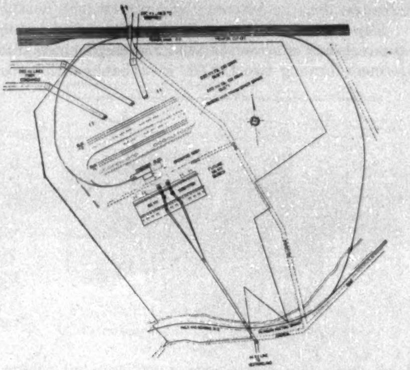

FIG. 8—PLOT PLAN OF THE PLYMOUTH MEETING SUBSTATION

The 220-kv. installation consists of two sectionalized buses, (Fig. 11) each line and transformer bank selecting either bus through oil circuit breakers. Provision is ultimately for seven lines and six transformer banks, of which three lines (two from Conowingo and one to the Siegfried Substation of the Pennsylvania Power & Light Company) and two 130,000-kv-a. transformer banks are being installed at this time. The oil circuit breakers are rated 1000-amperes, 187-kv., 2,500,000-kv-a. rupturing capacity. Each of the two Conowingo lines is provided with three 132-kv. potential transformers (the phase to neutral voltage of the 220-kv.

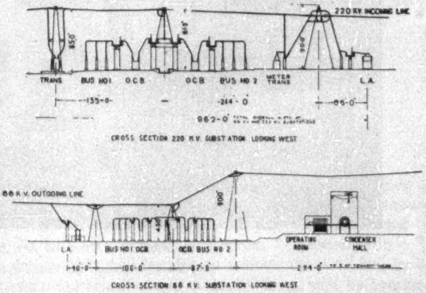

FIG. 9—PLYMOUTH MEETING SUBSTATION CROSS-SECTION

system being 127 kv.) These are used for impedance relays as well as instruments. The Siegfried line is provided with three combined current and potential transformer metering units, the potential elements of which are also used for relays and instruments. Each line is provided with a 220,000-volt auto-valve lightning arrester.

*Step-down Transformer Banks.* The initial installation consists of seven 43,333-kv-a. single-phase transformers forming two 130,000 kv-a. banks with a spare unit (Fig. 12). These transformers were originally rated at 33,333 kv-a. but will be increased in capacity by the application of air blown against the radiators. They have three windings: 220,000-volt, *Y*, 69,000-volt, *Y* and 13,300-volt, delta. The 13,300-volt tertiary serves the triple purpose of providing a closed delta for tap changing under load and for driving synchronous condensers. This tertiary is provided with a 33⅓ per cent tap for starting synchronous condensers. Transformers are equipped with inertaire equipment and weigh with oil 185 tons each. The tap changing under load has a voltage range of 15 per cent and in addition two five per cent taps are provided on the 220-kv. side.

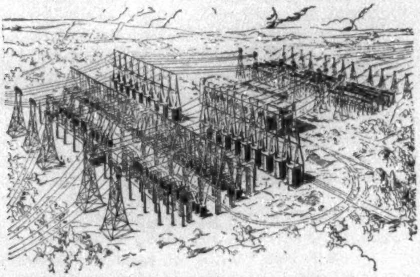

Fig. 10—Perspective Sketch—Plymouth Meeting Substation

Handling the heavy oil circuit breakers and transformers as well as the synchronous condensers was taken care of by a simple system of tracks shown on Fig. 8. A siding from the Pennsylvania Railroad extends in a wide sweep directly into the west end of the condenser building. At this point there is an assembly space large enough to hold a freight car and at the same time the complete transformer as is indicated in Fig. 13. In order to avoid excessive height for lifting the core of the transformer into its tank, a pit is provided in which the tank may be set and the core lowered into it. The transformer with the core inside is then raised to the floor level and its wheels put on the tracks which extend out into the switchyard. The 125-ton crane which is ample to lift the transformer with its core and oil, is also of ample capacity to lift the 30,000-kv-a. synchronous condensers. After the transformer has been completely assembled it is moved out of the building on its own wheels onto a transformer truck which is run to a point opposite the permanent location of the transformer, when the transformer is again moved on its own wheels into position. Numerous eyes are provided in the concrete in such a manner that hauling the transfer truck is readily accomplished by means of block and fall, and a small gasoline motor.

Switching off from the railroad track that leads into the condenser building is a track which extends through

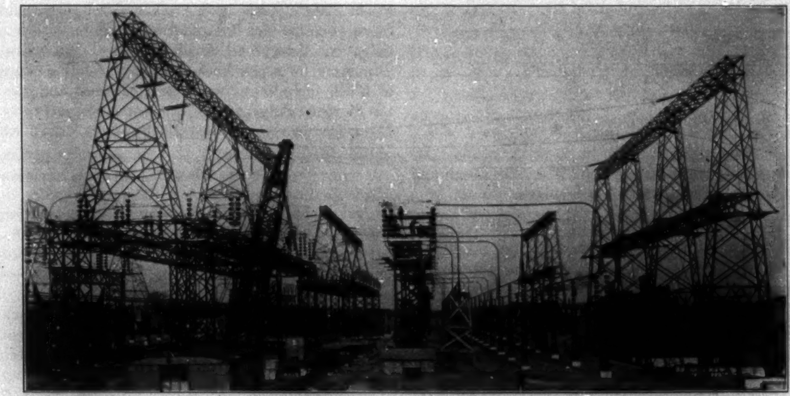

Fig. 11—General View of the 220-Kv. Yard During Construction

130,000-kv-a. transformer banks to the right, oil circuit breakers to the left.

the middle of the 220-kv. structure, which is used for handling the oil circuit breakers. Each single-pole element may be assembled in the condenser building and placed on top of a transfer truck; this in turn is placed on a second transfer truck. The breaker is then moved out to a position opposite its permanent location when the upper truck is rolled off the lower one until the oil breaker is in position. By means of jacks the breaker is lifted free from the truck and finally down on its I-beam foundations in a manner similar to that used at Conowingo. A track is also provided which will permit getting the potential transformers and metering units close to their location from which point they are skidded the short distance into position. It has been found on the initial installation alone the saving in handling heavy apparatus paid for the tracks and transfer cars.

*66-Kv. Substation.* The 66,000-volt substation is of practically the same design as at Westmoreland and the description of this latter given below will suffice. The only exception is that all of the lines at Plymouth Meeting are overhead, whereas most of those at Westmoreland are underground. Provision is made, however, for taking any of the lines from Plymouth Meeting out underground, though it is doubtful if this would ever be done. Initially this 66-kv. substation consists of sections for the two transformer banks, the two lines to Westmoreland and two lines to the Barbadoes Island Generating Station of the Philadelphia Suburban-Counties Gas & Electric Company at Norristown. Lightning arresters are installed on all four lines.

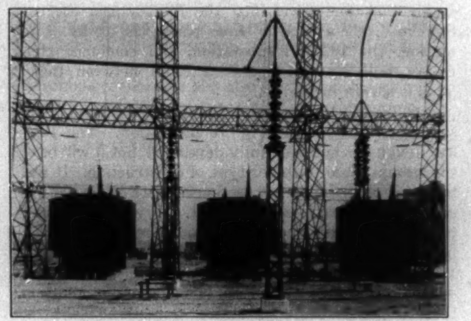
FIG. 12—130,000-KV-A., 220/69/13.3-KV. SELF-COOLED TRANSFORMER BANK

*Synchronous Condensers.* In addition to providing facilities for assembling transformers, oil circuit breakers, metering units, and potential transformers as described above, the condenser building is arranged to ultimately house six 30,000-kv-a. synchronous condensers. The building initially, however, is erected for three and three are being installed at this time.

These condensers operate at 600 rev. per min. and are provided with a scheme which gives extra high-speed excitation. This has been described in the technical press.[3] Each condenser is provided with a main 165-kw., 250-volt, six-pole, compound-wound exciter and a 40-kw., 250-volt, six-pole, compound-wound pilot exciter, one mounted on each end of the same shaft.

The condensers at this location are to be used primarily for stability purposes and will normally be carrying a light load. However, upon failure of one of the two Conowingo lines they will instantly supply the additional reactive kv-a. necessitated by one line operation as compared with two lines, and by holding up the voltage will materially stabilize the operation of the combined systems. This is accomplished by the regulator short-circuiting a resistance in the main exciter field causing the armature voltage to rise at a rate of 6000-7000 volts per sec. and applying a "ceiling" voltage of about 1000 on the nominal 250-volt fields of the condenser. It is planned to operate them normally at about 10,000 kv-a., though this may be varied in the light of operating experience. Under certain conditions they will be able to deliver about 55,000 kv-a. each and this increase of 45,000 kv-a. will be brought about in half a second.

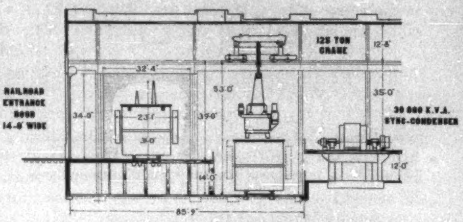

FIG. 13—PLYMOUTH MEETING SUBSTATION
Method of handling 43,333-kv-a., 220-kv. transformers

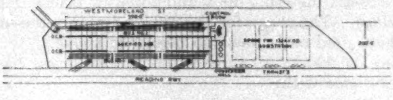

FIG. 14—WESTINGHOUSE SUBSTATION PLAN

The condenser starting and running oil circuit breakers are located outdoors between the transformers and the condenser building and from these are tapped

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3. "Super Excitation," D. M. Jones, *G. E. Review*, Dec. 1927, p. 580. "Super-Excited Condensers," O. A. Gustafson, *Elec. World*, Feb. 18, 1928, p. 349.

off two banks of transformers which step-down to a 110-220-volt system for light and power supply.

In an extension of the condenser building is located the operating room with pipe room beneath. The section now built houses all of the 220-kv. switchboards and those controlling the synchronous condensers. Ultimately when the 66-kv. substation is further developed the operating room will be double in size to house the additional switchboards. At present the few panels required for 66-kv. control are located at one end of the present room. Two storage batteries and two motor-generator sets are used for supplying 250-volt control and emergency lighting.

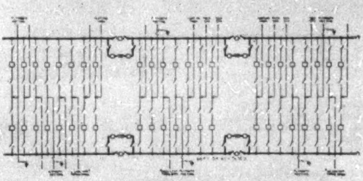

Fig. 15—Single-Line Diagram of Westmoreland Substation

To handle the large quantity of oil involved in this substation a separate building located a little distance from the main building and built partially under ground has been erected. In this house are located centrifuges, blotter press, oil pumps, and the system of valves and manifolds which will facilitate the rapid handling of oil. Five 12,000-gal. oil tanks mounted above ground are installed near this oil house and are used: one for clean circuit breaker oil, two for clean transformer oil, and two for dirty transformer or circuit breaker oil. Permanent supply and discharge pipes are extended to the 220-kv. circuit breakers and the transformers and to convenient points near the 66-kv. circuit breakers and 220-kv. metering units and potential transformers.

*Relays.* The relays for the 220 kv.-lines are the same as those used at Conowingo described above.

The 130,000-kv-a., three-winding transformer banks are provided with:

a. Three overload *C O* relays connected to current transformers located in the 220-kv. bushings. These will protect against phase-to-phase faults on 220-kv. bus, all faults on 66-kv. bus, and will act as back-ups to the 220-kv. phase-to-phase line relays.

b. Three special percentage differential *P Q Y* 28 relays with associated balancing current transformers. The large range of the ratio adjustment possible with these banks makes the use of a percentage differential relay necessary. The balancing current transformers combine the secondary currents from the 69- and 13.3-kv. windings and balance them through the relay against the secondary current from the 220 kv. side. They also serve to isolate electrically the current transformer circuits of the three windings, two of which are connected delta and the third star, and therefore, permit the use of standard grounding arrangement for the individual sets of current transformers. Due to the fact that there is no restraining action in the relay for transfer of power between the 69- and 13.3-kv. windings, it is necessary to use a special type of *P Q Y* 28 relay which is sufficiently insensitive to remain inoperative under the maximum possible case of such a power transfer, and also one which is sufficiently insensitive to prevent its operation on the initial rush of charging current when the bank is energized.

The 30,000-kv-a. synchronous condensers are provided with single winding *P Q* differentially connected relays.

The 66-kv. lines are equipped with duplex directional impedance *C Z* relays.

The station service transformer bank is protected by low energy overload *C O* relays.

### Westmoreland Substation

The Westmoreland Substation ties Conowingo and Interconnection power into the Philadelphia Electric System. It consists of three parts, the 66-kv. substation, the 13.2-kv. substation, and combined condenser building and operating room between them. This is shown in Fig. 14.

Figs. 15 and 16 give the single-line diagram and cross-section of the 66-kv. end of the substation. The 13.2-kv. design has not been fully developed, but it will be of the group-phase, outdoor type of construction. It will be noted that the 66 kv. section consists of double bus construction, each sectionalized at two points and provided for the future installation of reactors at these points. To each of the three sections themselves, two 100,000-kv-a. overhead lines from Plymouth Meeting will be connected or an ultimate of six, and in addition there is provision for a total of thirteen 50,000-kv-a. underground lines and four 80,000-kv-a. transformer banks, stepping down to 13,200 volts. The initial installation will consist of two lines from Plymouth Meeting, two lines to the Richmond Generating Station and two lines to the Schuylkill Generating Station, as well as two lines extending to some small (18,750 kv-a.) transformer banks at a nearby distribution substation, and two 80,000-kv-a. transformer banks. The oil circuit breakers are rated 800 and 1200 amperes (the latter on the Plymouth Meeting lines), 73 kv., 2,000,000

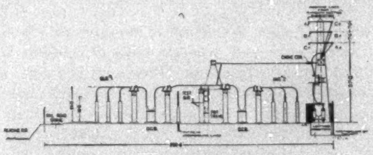

Fig. 16—Cross-Section of Westmoreland Station

kv-a. rupturing capacity. Lightning arresters are installed on the Plymouth Meeting lines. The relay protection consists of directional impedance *C Z* relays on all lines both overhead and underground, and differential *P Q*-21 with back-up overload *C O* relays on transformer banks.

The condenser building is laid out to house ultimately three 30,000-kv-a. synchronous condensers. They will be connected to the 13,200-volt bus bars and started by means of auto transformers. Two are being installed initially, operated at 720 rev. per min. It was felt that the speed of excitation on these units need not be quite as fast as those installed at Plymouth Meeting. However, fairly high speed is desired and this is provided.

While the weights to be handled at this substation are not as great as at Plymouth Meeting, nevertheless it was felt advisable to select a piece of land adjacent to a railroad and the present site with a siding from the Reading Railroad was decided upon. The siding extends along one side of the 66-kv. substation, through the end of the condenser building, on into the 13.2-kv. substation. A 100-ton crane in the condenser building will be used not only for assembling and repairing the synchronous condensers but also the transformers and other 66-kv. and 13.2-kv. equipment, which equipment can readily be brought into the condenser room by means of the above railroad siding and a transfer car.

Both the 66-kv. and 13.2-kv. sections as well as the condensers are controlled from one operating room which is part of the same building as the condenser room. This operating room is provided with a pipe room beneath. Adjacent and also part of the same building is an extension in which will be provision for 300,000-volt kenotron test set, offices, battery rooms, etc. A 15-kv. test set consisting of a transformer with ratio changing under load will be installed outdoors.

The 250-volt emergency lighting and control system consists of two 152-ampere-hour storage batteries and two 9-kw. motor-generator sets.

An oil handling system consisting of pumps and filters (both centrifuge and blotter presses) is provided, together with two 4500-gal. tanks located above ground, one for clean and one for dirty 66-kv. circuit breaker oil. Other tanks will be provided for the transformer banks. Supply and discharge pipes are extended conveniently to the 66-kv. breakers and directly to the transformers.

## Discussion

For discussion of this paper see page 906.

# 220-Kv. Transmission Line for the Conowingo Development

BY P. H. CHASE[1]
Member, A. I. E. E.

***Synopsis.***—*Current from the Conowingo plant is carried fifty-eight miles to the Plymouth Meeting Substation of the Philadelphia Electric Company over two 220-kv. single-circuit steel-tower transmission lines. These lines are carried on a right-of-way which provides space for a third future line. The conductors are 795,000-cir. mil steel-reinforced aluminum. Each circuit is shielded by two 183,000-cir. mil aluminum steel-reinforced ground wires. The insulator strings consist of 14 high-strength units in suspension position and 16 units in strain position. Conductors and ground wires are carried in a new type of slip clamp in order to decrease the unbalanced longitudinal stresses on the towers in the event of wire breakage. In general, foundations are of the earth grillage type. The tower design includes a number of novel features, among them the use of combination extensions to meet flexibly the varying topographical conditions, and the narrow waist immediately below the basket.*

FOR ultimate development, the 58-mi. transmission line to Philadelphia from the Conowingo hydroelectric plant on the Susquehanna River will consist of three 220-kv. single-circuit tower lines, each circuit supported in horizontal configuration. For the initial development two of the tower lines have been constructed.

The location of the Philadelphia terminus of these lines, the Plymouth Meeting Substation, approximately 15 mi. northwest of the center of Philadelphia, was determined by a number of factors, among them the practicable transmission routes into the main 66-kv. transmission system of the Philadelphia Electric Company, and the 220-kv. transmission line routes for interconnection with Pennsylvania Power and Light Company and Public Service Electric and Gas Company of New Jersey.

The location of the right-of-way is shown in Fig. 1. That portion of the right-of-way south and west of the crossing of the Pennsylvania Railroad at Glenloch passes through a fairly level farming country. North and east of Glenloch, the right-of-way follows the general direction of the railroads through Chester Valley, a natural channel leading to the Schuylkill River between Conshohocken and Norristown; thence to Plymouth Meeting Substation. This portion of the right-of-way passes through land of the highly-developed estate type.

After determination of the general location of the right-of-way by ground reconnaisance, an airplane map was made of a strip from 1½ to 3 mi. wide, to a scale of 1000 ft. to the inch. The airplane maps were used as a basis for the final location of the line and the determination of property owners and their holdings, from which final options were prepared for negotiation with owners of record. All these steps were taken prior to any negotiations or survey activities in the field. The right-of-way was secured on the principle of easements, being preferable to purchase in "fee simple."

The width of right-of-way was determined on the basis of accommodating three single-circuit tower lines, as shown in Fig. 2. The horizontal spacing between the conductors on a tower was largely determined by the clearance from the live hardware to the steel work, with the insulator strings deflected by wind and angles. A consideration of these factors resulted in a separation between conductors of 25 ft. 6 in. on tangent towers. In determining the distance between adjacent tower lines of 85 ft., or a distance of 34 ft. between adjacent wires, consideration was given to the safety

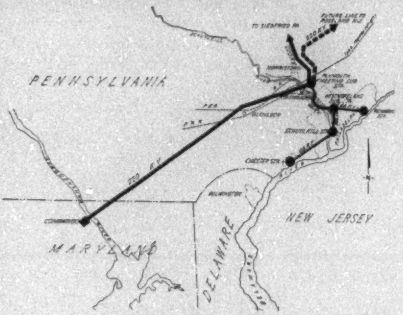

FIG. 1—ROUTE OF LINE

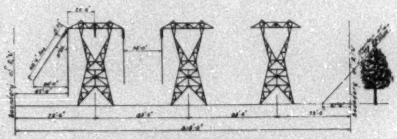

FIG. 2—CROSS-SECTION OF RIGHT OF WAY

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[1] Engineer, Transmission & Distribution Division, The Philadelphia Electric Company.

*Presented at the Baltimore Regional Meeting of A. I. E. E., Dist. 2, Baltimore, Md., April 17-20, 1928.*

of men working on a line adjacent to one in operation, conductor side-swing at center of span, and tower-offset.

The distance from each outside conductor to the edge of the right-of-way was determined by the amount of side-swing from wind, to which was added an additional factor for clearance.

In addition, a tree danger zone was considered to exist above a line starting from a point 45 ft. from the center line of the outside towers and extending upward and outward at an angle of 45 deg. Trees in this zone have been removed or trimmed.

### BASIS OF DESIGN

The following types of towers were used on the line:

Type A—Standard suspension tower, suitable for angles up to 1½ deg., 1100-ft. span.

Type B—Railroad crossing and angle tower, suitable for crossings, angles up to 6 deg., and tangent spans up to 2000 ft. This type, with a special top extension, was used for transpositions.

Type C—Angle tower, suitable for angles from 6 to 15 deg., and spans up to 1100 ft.

Type D—To be used for angles 15 to 60 deg., dead ends, and tangent spans up to 2500 ft.

In general, the line is designed to withstand a climatic loading of one-inch ice, but for unbalanced longitudinal load on the Type-A standard suspension tower, a tension in the conductor was taken corresponding to a load of ½-in. ice, it being obviously uneconomic to design for more severe conditions. Therefore, in order to minimize the stresses to which the tangent towers might be subjected under extraordinary conditions, a clamp of the releasing type was developed, to limit the maximum unbalanced longitudinal load on the tower to approximately 10,000 lb. Heavier ice loading was given consideration in the design of all types of towers for certain check conditions.

The design loads for the towers were calculated under the various assumed conditions of ice and wind for longitudinal, vertical, and transverse loading. These figures were increased by safety factors, thus giving maximum loads which the structural work of the towers was designed to withstand, using unit stresses shown in Table I.

The Type-B tower was designed to meet the requirements of General Order No. 13 of the Public Service Commission of Pennsylvania, which permitted its use for long tangent spans under non-crossing conditions when working to the allowable stresses in Table I.

The clearance diagram for the Type-A standard suspension tower is shown in Fig. 3. The clearance diagram was based on an ultimate string of 16 units and an arc control device having a probable transverse dimension of 24 in., and so located in the tower as to result in a normal clearance of 8 ft., a first accidental clearance of 6 ft. and a second accidental clearance of 5 ft. The first accidental clearance was on the basis of an 8-lb. wind, and the second accidental clearance on a 12-lb. wind, both without ice. Due to the lack of sufficient information on the probable shape and size of an effective arc control device, it was recognized that these accidental clearances might turn out to be liberal, but on the other hand, an arc control device larger than was assumed might be installed.

TABLE I

*Allowable Unit Stresses:*

Limiting values of slenderness ratio:

150 for corner posts
200 for web (computed stresses)
250 for braces (no computed stress)

Compression

$38{,}000 - 165\,\frac{l}{r}$ for values of $\frac{l}{r}$ up to 155,

maximum 28,000

$28{,}000 - 100\,\frac{l}{r}$ for values of $\frac{l}{r}$ from 155 to 250

Tension
30,000 on net section

Bolts
22,500 shear
45,000 bearing

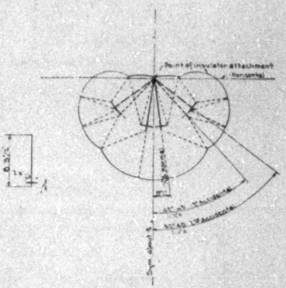

FIG. 3—CLEARANCE DIAGRAM FOR TOWERS, TYPE A

The length of span, height of tower, strength class of insulators, and characteristics of conductor must all be considered as a group, in order to determine the most economical combination and still maintain the most reliable service conditions obtainable. The size of conductor was determined by the electric loading conditions. This resulted in a conductor of 795,000-cir. mil aluminum steel-reinforced with a 40 per cent steel core, approximately 1¼ in. over-all diameter, which satisfied the corona requirements.

The conductor diameter being thus determined, and the ground clearance controlled by safety conditions, the over-all economics of tower height and span length were considered by studying various heights of towers, and for each height, increasing or decreasing the span to meet the catenary of the wire under consideration. The minimum ground clearance was 29 ft. 6 in.

## Towers and Foundations

Fig. 4 shows the assembly of the Type-A suspension tower. It is designed for one three-phase 220-kv. circuit,—the conductors in a horizontal plane with a separation of 25 ft. 6 in. Two ground wires are carried approximately 16 ft. above the plane of the conductors and midway between them. The lower section of the tower is square, so that the batter of the legs is the same in any face, resulting in a pyramidal section up to a point about 20 ft. below the conductors, where the sides flare outward to provide the necessary clearance for the middle conductor.

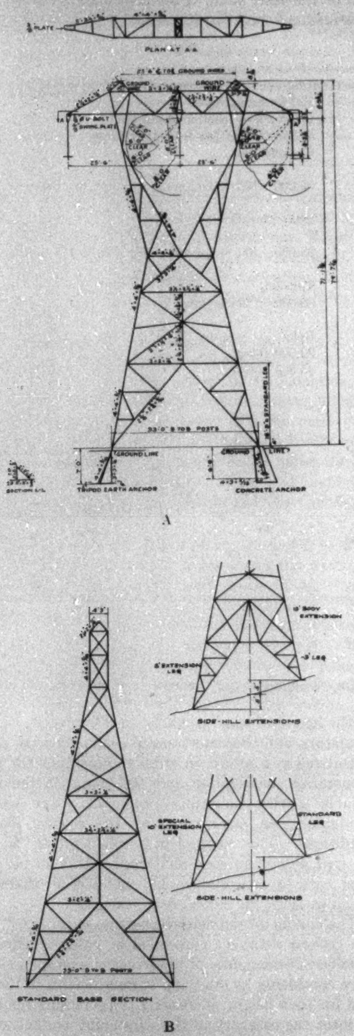

Fig. 4—Type-A Suspension Tower

Particularly on account of the size of the base, which is about 35 feet square, horizontal members close to the ground line are undesirable. To avoid this, the lower section is composed of four legs, each of which is independent, and may be made of any suitable length for small extensions and for uneven ground conditions. The standard legs are about 18 ft. in height, resulting in an 80-ft. tower, but special legs, both 5 ft. shorter and 5 or 10 ft. longer, have been used. As the connections are standard, any of these legs may be used on any one of the four corners of the tower.

For extensions greater than 10 ft., an additional section is inserted in the tower above the legs. By the use of the 15- or 30-ft. body extensions, the height of the tower may be increased by 5-ft. intervals to 125 ft.

Several new features of economic value are embodied in the tower. Maintaining the square horizontal section to as great a height as possible, (to the waist line) equalizes the distribution of the torque stresses in each of the four faces of the tower below the waist. The unbalanced horizontal shear at the foundation is reduced to a minimum by fixing the legs at an angle such that if extended above the waist line they would intersect at the center of gravity of the loads. The fact that the stresses are mainly in the tower legs permits very long equal or unequal leg extensions of the same size angle.

The net result is a tower and foundation that will have the lowest weight and cost for construction for the same loading-end strength, involving horizontal arrangement of conductors.

The towers are built from galvanized structural steel shapes, the largest main member for the Type-A suspension tower being 4 by 4 by 3/8-in. angle. Connections are all field-bolted with 5/8-in. galvanized bolts. The weights of all types of towers, extensions, and anchors, are shown in Table II.

For foundations, two designs were used; for normal line construction, a structural steel tripod anchor extending 7 ft. below ground; for special construction, a concrete foundation into which is placed an extension of the main leg angle. These two anchors for the Type-A suspension tower are also shown in Fig. 4.

There are three tranposition points, located at $^1/_6$, $^1/_2$, and $^5/_6$ points along the line. Fig. 5 illustrates the method of construction. There is a total of 520 towers, inclusive of the Susquehanna River crossing towers, in the 57.7 mi. of line.

Particularly because the design of this tower involved a number of novel features, load tests were made in order to check the soundness of the design assumptions. The tests verified the asumptions satisfactorily.[2]

TABLE II

Tower Weights

*Type A Tower—*

| | |
|---|---|
| Standard top section | 12,450 lb. |
| Standard "W" legs | 560 lb. |
| 5 ft. short "X" legs | 470 lb. |
| 5 ft. longer "Y" legs | 750 lb. |
| 10 ft. longer "Z" legs | 900 lb. |
| 15 ft. body extension | 3,540 lb. |
| 30 ft. body extension | 7,670 lb. |
| Earth anchors per set | 1,570 lb. |
| Concrete anchors | 430 lb. |

*Type B Tower—*

| | |
|---|---|
| Standard top section | 18,420 lb. |
| Standard "W" legs | 1,070 lb. |
| 5 ft. short "X" legs | 880 lb. |
| 5 ft. longer "Y" legs | 1,340 lb. |
| 10 ft. longer "Z" legs | 1,610 lb. |
| 15 ft. square extension | 4,830 lb. |
| 30 ft. square extension | 11,150 lb. |
| 45 ft. square extension | 18,700 lb. |
| 60 ft. square extension | 26,700 lb. |
| 75 ft. square extension | 36,100 lb. |
| Earth anchors per set | 2,180 lb. |
| Concrete anchors | 670 lb. |

*Type C Tower—*

| | |
|---|---|
| Standard top section | 20,620 lb. |
| Standard "W" legs | 1,060 lb. |
| 5 ft. short "X" legs | 950 lb. |
| 5 ft. longer "Y" legs | 1,400 lb. |
| 10 ft. longer "Z" legs | 1,660 lb. |
| 15 ft. square extension | 5,210 lb. |
| 30 ft. square extension | 11,400 lb. |
| 45 ft. square extension | 18,360 lb. |
| Earth anchors per set | 2,650 lb. |
| Concrete anchors | 800 lb. |

*Type D Tower—*

| | |
|---|---|
| Standard top section | 28,920 lb. |
| Standard "W" legs | 1,990 lb. |
| 5 ft. short "X" legs | 1,680 lb. |
| 5 ft. longer "Y" legs | 2,480 lb. |
| 10 ft. longer "Z" legs | 3,000 lb. |
| 20 ft. square extension | 10,450 lb. |
| 40 ft. square extension | 22,300 lb. |
| 60 ft. square extension | |
| Earth anchors per set | 10,700 lb. |
| Concrete anchors | 6,200 lb. |

The size of the foundation excavations made it practicable to use a newly-designed tractor crawler crane with ¼-yard clamshell bucket, shown in Fig. 6, which decreased the actual cost of excavation.

## CONDUCTORS AND GROUND WIRE

The characteristics of the conductor and ground wire are shown in Table III.

TABLE III
CHARACTERISTICS OF CONDUCTOR AND GROUND WIRE

| | Conductor | Ground wire |
|---|---|---|
| Size, A C S R— | 795,000 cir. mils | 183,600 cir. mils |
| Per cent steel core | 39.5 | 73.4 |
| Stranding | 30 by 0.1628 in. Al.<br>19 by 0.0977 in. Steel | 18 by 0.1010 in Al.<br>12 by 0.1214 in. Steel |
| Diameter | 1.140 in. | 0.707 in. |
| Weight per ft | 1.234 lb. | 0.6475 lb. |
| Ultimate strength | 37,900 lb | 25,700 lb. |
| Elastic limit | 27,300 lb. | 20,100 lb. |
| Tension at assumed maximum load (1 in., 8 lb., 0 deg. fahr.) | 18,845 lb. | 14,090 lb. |
| Tension at 60 deg. fahr | 6,180 lb. | 3,880 lb. |
| Tension at pre-stretch | 18,845 lb. | 14,090 lb. |

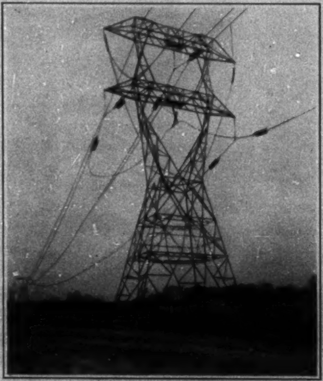

FIG. 5—TRANSPOSITION TOWER

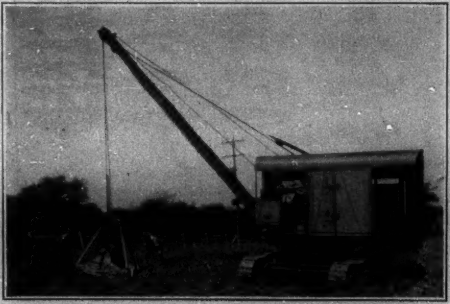

FIG. 6—CATERPILLAR TRACTOR CRANE

Considerable study was given to the characteristics of the steel-reinforced conductor, and the operating experience from all the major companies was carefully considered with special reference to eliminating troubles which have arisen in some cases from vibration of the conductor. Considerable investigation work has been done, both by the Philadelphia Electric Company, and the Aluminum Company of America in attempting to solve this problem. Investigation work indicated that when a metal is not under an appreciable initial strain it can withstand vibration practically indefinitely, but that its ability to withstand vibration decreases as the initial strain increases. This principle also applies to the aluminum strands of a cable.

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[2] See article by R. W. Wilbraham, "Load Test Check Tower Design," *Electrical World*, Nov. 12, 1927.

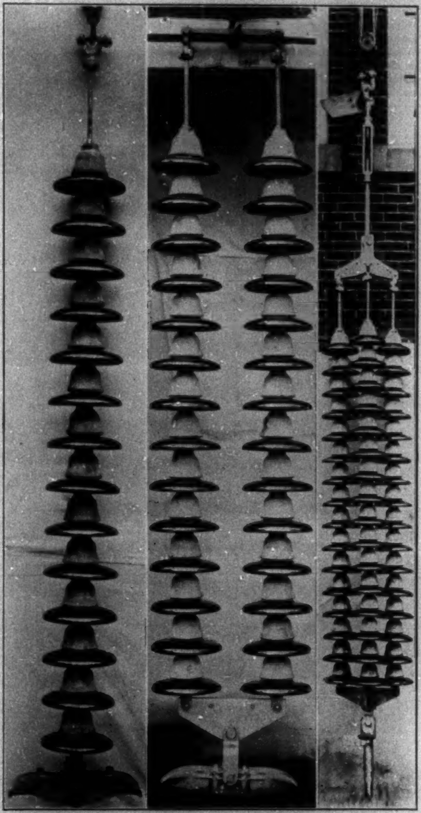
A B C

Fig. 7—Insulator Strings and Clamp

Further investigation work on the modulus of elasticity of the finished cables has shown that the modulus depends upon the maximum tension which the cable has withstood. This is due to the fact that as the cable is stretched under tension the aluminum strands first share the strain with the steel until they are stretched beyond their elastic limit, at which time they take a permanent elongation. As the strain on the cable is released, the steel core, due to its greater elasticity, begins to pick up the strain and relieve the aluminum strands. This indicates the advisability of prestretching the cable. This pre-stretching secures two advantages, the first of which is indicated above in obtaining the reduction of the stress in the aluminum strands, and the second is that it establishes the modulus of elasticity of the cable, so that its characteristics, and consequently the sag, will not vary when the cable is subjected to a heavy ice and wind loading.

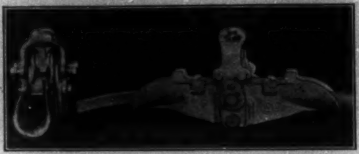
Fig. 8—Release Clamp

In a cable having a content of about 40 per cent by weight of steel, stress-strain curves show that after prestretching there is practically no tension in the aluminum strands under the ranges of temperature which usually exist at those times when vibration is most severe, namely, in fairly cold weather and with light winds. Experience has shown, further, that in practically every case where trouble has been experienced with broken strands, the steel content has been in the neighborhood of 25 to 30 per cent, and no strand failures with the 40 per cent content have been reported.

Fig. 9—Non-Releasing Clamp

In selecting the ground wire, it was concluded that it should be of the same general nature as the conductor, so that both materials would act in the same manner in unloading ice coatings; also that they should have approximately the same sag and swing characteristics. As an aluminum steel-reinforced cable was selected for the conductor, the same type of cable was selected for the ground wire.

Consideration also was given to securing a ground wire having sufficient current-carrying capacity to meet the requirements of lightning protection, and also to distribute any currents which might flow into the tower under the condition of an insulator flashover. It would have been possible to meet the above requirements with an all-steel galvanized cable, but a layer of aluminum strands outside the steel core has a preservative effect on the galvanizing, and consequently a cable with a steel core of approximately the same size as the conductor and carrying two layers of aluminum strand, was finally selected.

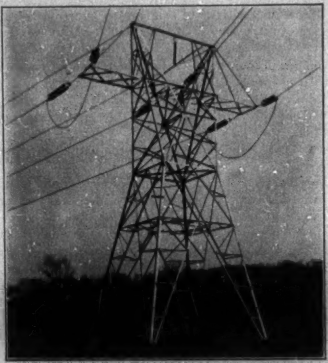

Fig. 10—Dead-end Tower and Jumper Construction

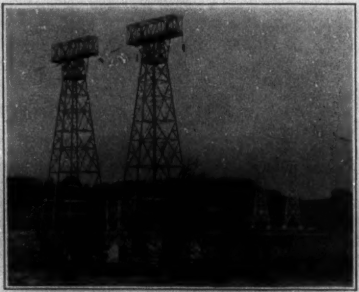

Fig 11—Susquehanna River Crossing

### Insulators and Hardware

The line is insulated with high-strength 10-in. disk insulators with 5¾-in. spacing. The design provides for an ultimate of 16 units for single and double suspension strings and 18 units for triple dead-end strings. The initial installation is with 14 units in suspension and 16 for triple-yoke strings, with a spacer link next to the tower having a length equal to two insulators, so that the conductors in every case are in the ultimate position.

The single, double, and triple string assemblies are shown in Fig. 7.

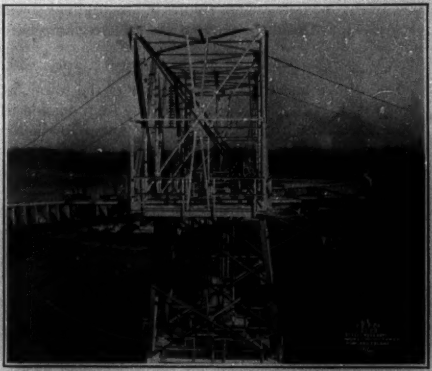

Fig. 12—Susquehanna River Crossing

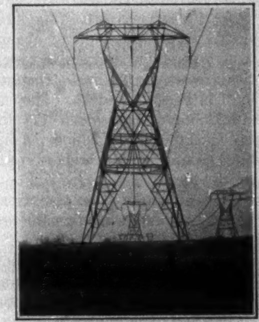

Fig. 13—Typical Line Construction

Except at points of special construction, the conductor and ground wire are carried in a releasing type of clamp, shown in Fig. 8. For special suspension construction, a non-releasing clamp as shown in Fig. 9 was used. Both clamps are of galvanized cast steel. In order to reduce the vibration-reflecting characteristics of the clamp they are free to swing in a vertical plane about an axis intersecting the axis of the conductor.

The releasing clamps are so designed that an unbalanced pull which will produce a longitudinal swing of 20 deg. of the insulator string will completely release the clamping mechanism. The wire is then held only by the friction in the saddle of the clamp. By the use of these clamps the longitudinal pull from a broken wire is restricted to a small fraction of the strength of the wire and under heavily loaded conditions should not exceed 5000 lb. This results in longitudinal tower stresses considerably less than if the release clamp were not used.

On the dead-end towers, the middle conductor is carried above and through the center of the tower, as shown in Fig. 10. The great distance from outside to outside of insulator string, for the center conductor made it impossible to support the jumper with a suspension string in the center and avoid the stranded conductor sagging to such a point as to decrease the clearances below safe limits. In order to maintain an economical design of tower top, recourse was had to carrying the stranded aluminum conductor in a 3-in. aluminum pipe, 24 ft. long. To each end was attached an aluminum reducing coupling carrying a 3-ft. extension of 1½-in. aluminum pipe from the end of which the conductor dropped free into the 90-deg. compression aluminum dead-end fitting.

Provision has been made for the attachment of arc control devices. A decision has been made to install some form of arc control device in the near future.

The transmission lines leave the power house on the west bank and are carried to the east bank in two spans —1450 and 2200 ft., respectively. The intermediate towers are located on an island in the channel of the river, and act as a dead-end and single tower, greatly diminishing the stresses on the roof structure. These towers are shown in Figs. 11 and 12. They are 228 ft. high (above the foundations), weigh 113 tons each, and have a base spread of 60 ft., supported on concrete piers 20 ft. above ground, with a bridge-type walk-way interconnecting the piers.

To provide communication from the river bank to these towers at times of high water, a cable-way of 1½ tons capacity has been installed.

The towers are of structural steel, the lower two-thirds riveted for rigidity, and painted with aluminum paint. The upper third is galvanized structural steel, bolted, in order to avoid maintenance painting adjacent to live parts. On the top bridge, on the crossarm of the towers, permanent rigging-booms have been provided, in order to facilitate maintenance operations.

The author wishes to express his appreciation of the helpful assistance in the preparation of this paper which was given by Mr. R. W. Wilbraham of the Day & Zimmerman Engineering & Construction Co. and Mr. W. W. Woodruff of The Philadelphia Electric Company.

# Discussion

## THE CONOWINGO DEVELOPMENT

(Wilson, Hentz, and Chase)

Baltimore, Md., April 19, 1928

**F. G. Baum:** The interesting thing about the Conowingo power station itself is the speed at which the work was done. It would have been very interesting if the authors had added the cost of this development.

I had occasion last year to look over a hydroelectric project in a foreign country where they had $6,000,000 to spend on the job, a much easier piece of work than this, and the job was laid out to be done in four years. I told them that they were losing two years in output and two years in interest charges.

The total result of the comparison is this, that while labor costs are about one-third of ours, when they get through building a power plant they have about as many dollars in the job as we have here. This results largely from the extra time taken to do the work.

I am very happy to see the eastern engineers finally coming to 220-kv. transmission. I believe that under that voltage we haven't any real transmission voltage, because the amount of power you can get even over a 110-kv. line is so small it is really a distributing line. We have had now, in northern California, five years' experience with 220 kv. Starting with 11-kv. lines built 30 years ago and extending up gradually to the 220-kv., the 220 was the first line we built that surpassed our expectations. Previous to that we were always more or less disappointed in our transmission results, and not only in the amount of power but in the security of service. Very often it is figured that the exposure from service interruption depends on the number of miles of exposure, but what you really are interested in is the number of interruptions, say, per million kw-hr. delivered, and that certainly is going to be much less at 220 kv. than at 110 or lower voltages.

I believe that the system adopted for this transmission was the one solution which was right; that is, the decision for a *constant* voltage system brought about by synchronous condenser voltage regulation.

**F. C. Hanker:** The problem of the Conowingo System is largely one of insuring, in so far as possible, continuity of supply to the ultimate user. That problem, when you come to the larger power plants, located some distance from the load center, involves the additional link of transmission. As Mr. Baum has pointed out, the records on the Coast have shown very satisfactory results on the higher voltages. There has not been the same period of operation in the East, but surely, with the amount of engineering talent applied to the problem, we can expect that after some of the initial troubles are overcome satisfactory service will be secured.

In the Conowingo Development, fortunately, we had the benefit of a number of years of analytical work and field testing combined with the experience on the pioneer work of the West on longer lines. The studies indicated that a very considerable improvement in the operating results could be obtained by special characteristics in the apparatus to improve operating stability.

Those improvements in the characteristics of the apparatus have been made possible to a greater extent on some of the Coast propositions where the generating capacity and the accompanying equipment do not represent as large a percentage in the total investment. In those cases you can afford to put considerably more expense into apparatus than in the ordinary case where the generating and regulating apparatus is a smaller proportion of the total cost.

There has been theoretical discussion on load limitations of systems and the problem is becoming more generally recognized. What we need now is more operating experience with apparatus having improved characteristics and the results of the next few years will show the justification for the expense involved.

**R. L. Thomas:** Mr. Wilson in his paper has referred to one feature of the Conowingo development which is perhaps unique, namely the backwater or pond-level agreement with the Holtwood development of the Pennsylvania Water & Power Company. The details of this arrangement belong in the field of civil rather than of electrical engineering but a number of questions has been asked and a brief statement regarding the scheme may be of interest.

The Holtwood Development is located in Pennsylvania about 15 mi. upstream from the Conowingo Development. When the Pennsylvania Water & Power Company took over this development and completed the initial installation in 1909 and 1910, the tailrace as planned was already completed. The plant has been located at the upper end of an island, forming a natural tailrace consisting of a very irregular, deep, and narrow channel about two-thirds of a mile in length. When unwatered it looked like a gorge. No improvements had been made on it. Below this natural channel there was originally a reef which formed a rapids about half a mile long, ending in another deep pool. These deep pools are rather characteristic of the Susquehanna. Through that reef the McCall Ferry Power Company had cut a canal, but they left what amounted to a flat rock weir at an elevation of 101½ ft. above mean sea level for the purpose of sealing the draft tubes of the turbines. Also their canal was designed for a flow of 20,000 cu. ft. per sec., whereas the Holtwood power house, as subsequently developed, actually discharges 30,000 sec.-ft. at full load. This increased discharge and the naturally poor hydraulic characteristics of the tailrace resulted in a maximum drop through the tailrace of about 14 ft. at full load with no water flowing over the Holtwood Dam. This represents a lot of power, and obviously it was economical to try to regain as much of it as possible.

In 1916 the company started on an ambitious excavation scheme, calling for a large amount of subaqueous rock excavation. Naturally the power house could not be shut down and on account of the swift current the work involved was expensive and difficult. It was suspended in 1917 on account of the War. About the same time studies were being made of the Conowingo project, the estimates being based on a clear-crest dam with crest at an elevation of about 100 ft. above mean sea level. Studies made at that time showed that a method of developing the loss in the Holtwood tailrace more economically than by excavation would be to superimpose steel gates or a movable dam of some kind on the Conowingo dam so as to maintain a water level there considerably higher than had been contemplated previously, and thus back water into the Holtwood tailrace and partially "drown out" the rapids there with, of course, some consequent loss in head at the Holtwood plant. In effect the proposition was to transfer a varying amount of head from one plant to the other. Roughly, the general order of magnitude of the ratio of gain at Conowingo to loss at Holtwood was about 10 to 1.

Those studies were made on the assumption that both projects would be controlled by the same interests. Later when the Conowingo project was undertaken by the Philadelphia Electric Company, engineers of both companies made exhaustive studies and again showed that there was a very considerable gain to be accomplished by maintaining a pond level at Conowingo considerably higher than would be allowable under a scheme which would permit no interference with levels at Holtwood, or under a scheme adhering to the provisions of certain agreements made years before. A dam of this type is logically a movable-dam proposition, as property or flowage rights must be acquired anyway to elevations above the maximum flood levels. Also when the Conowingo engineers adopted the lower site at Conowingo it was found that a movable dam or gates of some type were almost necessary, or at least economical, in order to hold down the pond level at time of maximum flood to such an elevation as would permit a feasible railroad grade from the Conowingo dam down to Perryville.

An arrangement was finally entered into between the two companies whereby the lower company maintains a pond level not to exceed 108½ ft. above mean sea level. This amounts to a sale of raw water power, you might say, from one company to the other, and I think both companies are going to account for it as a sale of power. The lower company pays the upper company its loss (meaning the loss under the present tailrace conditions, and not the greater loss which would have obtained if the excavation had been carried out) plus a share in the gain at Conowingo. It is a good proposition for both companies, and obviously it is in the interests of conservation of natural resources, because the desideratum is to get the most possible energy out of the Susquehanna River from the Holtwood pond to the Conowingo tailwater, and various computations have shown, depending upon what assumption is made, that the over-all, average net annual gain is from 84,000,000 to over 100,000,000 kw-hr.

Now the overlapping of heads between plants on the same stream, and operated by the same company, is not new, as it has been practised by several companies in recent years, but I believe that such an arrangement between two independent companies is unique, and it is gratifying that what was evidently a good engineering proposition could be put through in a business way.

The Gould Street engineers state that they adopted 440-volt auxiliaries in order to eliminate having two voltages and because the cost of the motors was actually less. I wonder if Mr. Hentz would care to say something on that.

As to the economic side, these papers make the situation clear. Before the Conowingo project was carried out there was available in the lower Susquehanna, from Holtwood down, a fall of about 100 ft., most of which was capable of development, but such development would be economical only if a market could be found which, first, would be large enough to permit of a great over-development of the river as compared with what is generally called firm power; second, would be large enough to absorb practically all of the available output from the start; and third, with a leak load sharp enough to give the hydro plant a high-capacity value. Baltimore, with a large existing supply of hydroelectric energy, did not offer such a market. Philadelphia did, especially with the transmission interconnections. It certainly is to the interest of the public that this power which has gone to waste for all time should be developed, thus saving, I believe Mr. Wilson stated, about 750,000 tons of coal a year.

**P. L. Alger:** I have been much interested in the design of four of the main Conowingo generators. They were so large that they were assembled completely at the plant, and no tests were made at the factory. I am glad to say they have gone into service without any important difficulty, and seem to be operating very well.

One of the novel features of the design of these machines is that the rotor rims are made of overlapping steel plates wrapped flatwise around the periphery, and the rotor spider arms are made of steel plates riveted together, so the entire rotor, except for the hub casting, is of plate construction. This is the first time, I believe, that such a construction has been employed. It has been described in a recent A. S. M. E. paper[1].

After the tests on the machines are completed, we hope to publish a paper giving the general dimensions and details of performance. At the present time, our expectations are that the efficiency at full load and 0.9 power factor under rated conditions, will be 97.5 per cent, although the short-circuit ratio is exceptionally high, approximately 1.4.

**D. W. Roper:** I should like to inquire from the authors of the papers if there were any special features in the contract which offered an inducement to the contractors to make speed?

**A. F. Bang:** I wish to offer a slight criticism of the high-tension switching layout at Conowingo. It may have been the most economical layout for the present to put all switches on top of the roof, but it seems to me that such an arrangement very decidedly limits the expansion possibilities. This would be especially undesirable in case at some future time it should be considered important to tie in another high-tension circuit, besides those going to Philadelphia.

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[1] H. G. Reist, "Plate-Steel Rotor for an Electric Generator." Paper presented at the Spring Meeting, 1928, of the A. S. M. E. at Pittsburgh, Pa.

Another questionable feature seems to me the ever present danger of oil-switch fires. These will happen occasionally, as we all know, even with the best of modern switches. And in case they do happen, is there not appreciable danger to the extremely valuable equipment below, at least far more so than in a layout where the switching station is at some distance from the power house?

**Alex. Wilson:** As to the speed with which the construction work was completed, there were several contributing factors, one of which was good fortune in respect to damage and delays due to floods. While two of the floods which occurred during the period of construction exceeded the previous records for the respective months in which they occurred, the condition of the construction work at the time the floods occurred was in such shape that but little damage was done.

Another and probably the most important factor contributing to the speed of construction was the careful scheduling of all operations and rigid adherence to the schedules. These schedules went into great detail, scheduling issue of drawings and the ordering and delivery of material, as well as the actual operations of construction; the calendar period in which each operation must be performed was likewise clearly defined and from time to time as the work progressed, the progress schedules were revised and where gains were made in any of the major operations, the schedule of such operations was advanced.

No bonuses were offered to the contractors to make speed. All of the contracts were agency agreements under which the contractor received a fixed fee for his services.

Mr. Alger referred to the efficiency of the generators. The efficiency of the water wheels might also be of interest. At best gate, these wheels have an efficiency of about 92 per cent.

**R. S. Hentz:** Mr. Bang has asked why we put the substation at Conowingo on the roof. That was primarily a matter of economics. The contour of the land was such that we could not have erected a substation in any other place except by going up on top of the hill where a double-bus substation could be erected. We believe a fair degree of flexibility has been incorporated into this 220-kv. layout. There is provision for one more 220-kv. line, making three in all. As two lines will easily transmit the contemplated maximum ultimate development of the station there was no need to provide for further expansion. True, it would have been better to have had a double-bus layout similar to that at Plymouth Meeting, but it would have cost too much at Conowingo. Plymouth Meeting, in addition to controlling the power from Conowingo, also controls that from the interconnection, thereby making it of greater importance and fully justifying a double-bus layout.

In regard to the matter of oil fires, when a satisfactory switch is developed, not using oil, we will be very glad to look at it. However, oil switches are with us and we have to use them. In the case of the 13,800-volt switch structure, the building has been divided into several comparments by smoke-proof barriers, thus confining any oil fires that may occur.

In regard to the lightning arresters, there is one other factor I think was not touched upon. The generators are provided with over-speed and over-voltage devices, (the over-speed is mechanical). These two devices have their contacts in parallel, so that the closure of either will trip the generator breaker. This is necessary to protect any motor driven equipment that might be left on those machines from damage due to excessive speed. This also protects the lightning arresters from very high voltages.

**P. H. Chase:** I was asked to say something about the lightning situation and the selection of the ground wires on the transmission lines. This matter of ground wires received consideration from many different angles. When we first started there was no operating experience with 220 kv. to help us on the lightning conditions in the East. The initial decision was to omit ground wires. However, before the project was very far under way there was some operating experience in the East, in northern Pennsylvania, and also considerably more information was developed from theoretical and experimental work which indicated the advisability of installing ground wires. The decision was therefore made to include ground wires. There have been various estimates as to how much the induced voltage would be reduced by the use of ground wires; as high as 50 per cent has been talked of. The percentage reduction in voltage is still largely a matter of speculation. I think that in another year we will be able to give quite conclusively the results as they affect operation. We have been through one lightning storm this spring that crossed the line without causing any trouble.

Mr. Hentz mentioned a high-voltage test. Observing the line during this test I was quite surprised that it didn't show much visible corona at 380,000 volts. There were streamers, spots along the conductor, and looking along the conductor one could see a bluish haze. Also there was a slight amount of corona on the line end of the strings. Photographs were taken of the insulator strings with quartz-lens cameras, taking advantage of the ultra-violet rays, but very little corona was in evidence.

It may be of interest to hear of a few questions that have come up since the line has been in service. A few weeks ago we got a complaint from one town that automobiles passing under the line were being "charged," and also that there was serious trouble with radio reception. It turned out that all those were unfounded and simply made good newspaper stories. The starting point was apparently trouble from some trolley circuit or something like that. Complaints have been received that the wires are dangerously close to the ground. When you stop to think of it, to the layman a conductor 1⅛ in. in diameter looks considerably nearer at 30 ft. than, say, a No. 6 A. W. G. wire.

Those were very amusing, although they had to be met and answered when our publicity people called them to our attention.

# The Communication System of the Conowingo Development

BY W. B. BEALS[1] and E. B. TUTTLE[2]
Member, A. I. E. E. Member, A. I. E. E.

***Synopsis.***—*This paper describes the communication system which has been installed to serve the power plant at Conowingo, Maryland, and its associated transmission line.*

*The important features to be considered in designing a telephone system for a power plant are pointed out. The types of telephone switchboard and telephone instruments chosen in this case to meet the special requirements of the generating station, together with the layout and cabling arrangement, are outlined.*

*The paper also discusses the possible ways of providing for the needs of the load dispatcher and the plan adopted at Conowingo; the facilities provided the patrolmen for calling from points along the transmission line; the connection from the private branch exchange to the general telephone system; and the special electrical protection installed on the long lines leaving the power house.*

## 1. INTRODUCTION

THE proper functioning of a power plant and distribution system depends to a large extent upon the ability of the operating force to communicate easily and promptly with one another. Therefore, the details of design of a power system may be influenced by a consideration of the various possibilities of telephone communication.

The design of a telephone system to meet the needs of a generating station such as that at Conowingo and the transmission network associated with such a system, requires the closest cooperation between the power and telephone engineers and a thorough understanding of each other's problems.

Among the important features to be considered in this cooperative work are:

a. Continuity of service.

b. Means for quick communication with any part of the generating station.

c. Location of telephones so that they can be used without taking power-house employees away from their working stations.

d. Means for communication between the generating station, system operator, and points along the transmission line.

e. Protection for the circuits connecting with the general telephone system.

All of the features in the above list were given very careful consideration in designing the telephone system for the Conowingo project.

The essential elements of such a telephone layout consist of a private branch exchange switchboard which provides convenient means for connecting a telephone in one part of the plant with a telephone in another location or with telephone central offices; telephone distribution cables running from the switchboard to the locations where the telephones are installed; circuits running from the branch switchboard to the central office of the telephone company; and finally, the telephones themselves so located as best to meet the needs of the people who are to use the system.

## 2. PRIVATE BRANCH EXCHANGE AND ASSOCIATED POWER PLANT

(a) *Conditions to be Met and Type Adopted.* The Conowingo power house is located within the area served by the Darlington, Maryland, Central Office. In the Darlington central office area, the service is of the magneto type (*i. e.*, hand generators are used for signaling and dry cells are installed at each telephone set to supply talking battery). In such an area it is usual to furnish private branch exchange equipment of the same type. At the Conowingo power house, however, in view of the size of the installation and the fact that it lends itself better to some of the rather special arrangements needed at certain places in the power house, it was decided to use the common battery type of telephone system where the telephone user signals the operator by simply lifting the receiver off the hook.

The adoption of the common battery type of private branch exchange in the Darlington central office area necessitated certain modifications in the usual type of switchboard in order to furnish lamp signaling and supervision and at the same time to operate on connections to the magneto central office switchboard at Darlington.

The operating battery consists of eleven cells of the enclosed radio type and is kept in a fully charged condition by a small, full-wave rectifier, operated from the local lighting circuit and adjusted to trickle charge the battery continuously. The battery has sufficient capacity to operate the telephone system for some time in case of trouble with the rectifier or the local lighting circuits.

Regular and emergency ringing interrupters are installed for supplying energy to ring the various tele-

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phone stations and the central office of the telephone company. A hand generator is also installed in the switchboard for emergency use.

Alarm signal equipment, consisting of a bell and lamps, is provided to indicate the operation of a charge or discharge fuse on the battery, the failure of the a-c. service or the burning out of a rectifier tube. Spare fuses and rectifier tubes have been conveniently located for replacements in case of failure.

(*b*) *Location and Layout of Private Branch Exchange Equipment.* The private branch exchange switchboard is installed in the main control room and adjacent to the power switchboard operator's desk, so that it can be operated by the power switchboard operator when desired. It is equipped for handling 70 common battery lines, 10 local battery lines and 5 central office trunk or long tie lines (such as lines to Philadelphia). Provision has been made for further trunk and tie line growth.

In the usual private branch exchange all relay and signaling equipment is contained in the telephone switchboard framework. The modifications at Conowingo required a number of additional relays and repeating coils which the switchboard would not accommodate. These relays and coils have been mounted on a small rack similar in design to those used in small telephone central offices. Since the ultimate layout of the main control room would not permit the installation of this rack adjacent to the telephone switchboard, it has been placed in another room as close as possible to the board.

From the telephone switchboard lead-covered cables extend to a cross-connecting main frame which permits the association of any cable pair in the distributing cables to the telephone stations, or, in the cable leading out of the power house, with the proper switchboard terminal. The distributing frame is of the type used in small telephone central offices and carries the standard telephone protectors. It has been located in the same room assigned to the telephone power plant. This room is close to the center of distribution of the telephones which will ultimately be needed and will, therefore, permit of the most economical distribution cable layout.

### 3. TELEPHONE STATION EQUIPMENT AND DISTRIBUTION CABLE

(*a*) *Requirements and Types Adopted.* As mentioned previously, the main requirements of the apparatus to be installed in the power station are simplicity of operation, durability and compactness. The first of these has been met by the adoption of common battery signaling equipment. To meet the second and third conditions the telephones have been placed in recessed cabinets in the walls. Each cabinet is designed to hold a standard desk stand and bell box and is provided with a door which lets down to serve as a shelf when the telephone is in use. When the telephone is not in use, the door is kept closed and the apparatus is out of the way in a protected location. This method of installation is general in the power stations and substations of the Philadelphia Electric Company.

At the gage board at each of the machines, under certain conditions it will be necessary for attendants to take orders over the telephone, read the meters, and adjust apparatus at the same time. In order to meet this condition and still avoid the possibility of having telephone apparatus in a position where it might be in the way, a jack has been provided at each of the gage boards, and operators' telephone sets with chest transmitters and head receivers with extension cords have been provided in convenient locations for use with the jack ended circuits. The jacks are enclosed in dust-proof boxes and are connected to two circuits terminating on the switchboard, one circuit terminating at the panels for service generators Nos. 1 and 2 and main generators Nos. 1 to 4 and the other circuit at the panels for present and future main generating units Nos. 5 to 11. With this arrangement the station attendants can talk over the telephone and yet have both hands free for whatever they are required to do.

Telephone stations have been provided along the dam for use in making reports from points in the vicinity of the gates. Since these stations are in locations which will always be subject to a certain amount of moisture, mine type sets have been installed in recessed cabinets located at convenient points along the parapet wall. These cabinets are provided with metal frames and covers and are kept locked in order to prevent use of the telephones by unauthorized persons. Mine type sets have also been provided on the observation platform near the spillway and in the inspection tunnel in the vicinity of the butterfly valves.

Five mine type sets have been installed on the steel framework of the substation located on the roof of the power house, some points of which are 85 ft. above the level of the roof. They provide a means of communication with men working on the 220-kv. disconnecting switches. Four additional mine type sets have also been installed at various locations on the roof of the power house. In addition to these telephones, four jack-ended circuits have been mounted inside of the mine type sets on the roof. Durable, moisture proof extension cords terminated at one end in a plug for connection to the jack-ended circuits and at the other end in a small jack box have been provided for the use of men working on the inside of the 220-kv. circuit breaker tanks. The jack boxes are arranged to be attached to the workmen's belt in order to leave both his hands free. A regular telephone operator's set with a short cord and plug is provided so that the workman may insert the plug in the jack box on his belt. This gives an easy means of communication between the men working in the circuit breaker tanks and men outside.

In the office bay, standard desk set equipment has been provided for office employees.

(*b*) *Cabling Layout.* In view of the conditions to be met in rendering telephone service in power stations, the telephone circuits are for the most part in lead-covered cable except that the runs from cable terminals to the individual stations are made with single pair twisted wire. These cables vary from 11 to 101 pairs each and are run through metal conduit, installed for this purpose when the concrete of the structure was poured. The telephone conduits are separated by several inches from the conduits carrying lighting and other distribution circuits in the power house, and are bonded to the power system ground so that in case of any faults on the power circuits it is expected that resulting voltages and stray currents will not introduce a hazard on the telephone circuits. The installation of telephone cables of the size employed in the power house necessitated placing "pull boxes" at frequent intervals along the conduit runs.

The distribution cables to the stations are terminated in five main terminal boxes where the individual cable pairs can be connected to the wires running to the various stations. This permits of considerable flexibility in cable pair assignments, and makes it possible readily to interchange cable pairs in case one becomes defective or to replace a short section of cable without interfering with the rest of the circuits in the telephone plant.

### 4. Outside Lines

(*a*) *Trunk Lines and Outside Stations.* The private branch exchange is connected with the telephone company's central office at Darlington, Maryland, by means of two circuits which are carried out of the power house in lead-covered cable and thence by open line wires to the central office. The same cable carries a few lines to stations located in the employees' houses not far from the dam.

(*b*) *Load Dispatching Circuits.* In any power transmission system the operations requiring coordinated action at power sources and substations make it imperative that communication be established quickly and maintained without interruption between the load dispatcher and the operating units.

As the system is extended to include more than one source of supply the necessity for this close supervision on the part of the load dispatcher is very greatly increased by the need for proper distribution of loads. This supervision may be secured by automatic operation or through communication with an operating force.

At the A. I. E. E. Midwinter Convention in Philadelphia in February 1924, two papers were presented describing apparatus for distant operating by mechanical means. The use of this equipment places in the hands of the load dispatcher the means of regulating generators and loads by his own personal actions and in certain cases generating plants and substations can be very satisfactorily operated in this manner. Associated with the mechanical operation of these systems there must be visual indication of their conditions by such means as distant metering, gaging, etc.

With power units and substations of such size as are involved in the Conowingo project, personal attendance becomes imperative for a number of reasons, and therefore system operation from a distant point through mechanical agencies was deemed not suitable for this installation.

Several methods which present themselves, *viz.*, telephone, telegraph, and printing typewriter were considered in setting up the load dispatching system for the Conowingo power project. The extensive existing load dispatching system of the Philadelphia Electric Company system had a great influence in deciding what extensions should be made to care for the interconnection with the Conowingo project. This existing system consists of private lines leased from the telephone company and connecting the various substations and generating centers with the general office building of the company. At this location the lines terminate in a magneto switchboard in the office of the load dispatcher who can thus secure instant direct contact with the various units of the system.

This system is reserved for the exclusive use of the load dispatching forces and no connection is provided to the telephone company's exchange system except through an emergency circuit on the board in the load dispatcher's office.

Direct telephone company facilities were, therefore, found most suitable in the extension to Conowingo of the load dispatching system. In planning this extension, two prime factors were considered to be highly important, continuity and reliability of service. To provide for the former, it was decided to supply both regular and emergency circuits routed through separate cables or over separate pole lines so that in the event of ordinary maintenance troubles which might affect one circuit, the second would be available. The reservation of both of these circuits for load dispatching exclusively is not warranted, and provision is made for one to be used between the private branch exchanges provided for general telephone business, but to be available to the load dispatcher by means of loop jacks in his private line switchboard. This latter arrangement permits the load dispatcher to take over the use of the second circuit and clear any conversation that it may be carrying.

The second requirement, reliability, presented the more difficult engineering problem, as it will in any similar situation. The telephone company had existing plant for the entire distance from the Conowingo site to the headquarters of the Electric Company at 10th and Chestnut Streets, Philadelphia, consisting of underground cable plant between Philadelphia and Havre de Grace at the mouth of the Susquehanna River connected to an open wire pole line from Havre de Grace to the power site. Underground plant is, of course, most reliable, but the open wire line may be interrupted during heavy sleet and wind storms.

The power company has a continuous private right-of-way from Conowingo to Plymouth Meeting. This right-of-way is free from trees and other obstructions, but proximity to the high-voltage transmission line rendered it unsuitable for communication circuits.

Various means of securing telephone service were studied, including carrier current systems on the power transmission lines and short wave radio. At the time this paper was prepared, consideration was being given to the desirability of building a new pole line on a private right-of-way, cleared of trees and shrubs, from Havre de Grace to the power site. The poles and wires would be so spaced and of such strength as to be capable of withstanding ice and sleet loads such as have been encountered in the past.

While load dispatching is of prime importance in setting up communication service, there are other important uses which cannot be neglected. Many routine matters of operation and maintenance can best be handled by telephone and facilities to do this must be provided. Many power companies do not feel that it is necessary to reserve the dispatching circuits exclusively for that service and use the same circuits for the transaction of general business. However, with the demand on the power companies for continuous service by trunk line railroads and city water supply systems, etc., the necessity of immediate communication for load dispatching purposes becomes more exacting. For this reason the Philadelphia Electric Company decided to provide a second circuit to care for general business and make this second circuit available in emergencies for load dispatching purposes as outlined above.

(*c*) *Patrol Stations.* Another important communication service is that provided for the use of patrolmen. Regular telephone service by means of telephone stations connected to the nearest central office of the telephone company offered opportunity for patrol service over the regular toll lines of the telephone system. With the increased speed of service now provided over these lines dependable and rapid connections can be obtained. This method has the advantage over a single patrol circuit, in that in case of failure of one toll line, alternate routes are available. If the number of patrol stations is small and the calls infrequent, this service is also less expensive.

This method was adopted for the Conowingo system and four patrol stations have been established between Conowingo and Plymouth Meeting, each with the telephone located in a building owned by the Power Company and located on its right-of-way.

(*d*) *Special Protection.* Preliminary computations indicated that at time of fault on the 220-kv. transmission line, ground currents of considerable magnitude would flow through the station ground connection, and even if the impedance of the ground connection were as low as a fraction of an ohm, there would be a considerable rise in ground potential in the neighborhood of the dam.

A rise in ground potential at the dam with reference to the ground at the other terminals of the circuits connected to the private branch exchange might operate the telephone protectors and result in interruptions to telephone service at times when it was most needed. These potentials would also be effective between the telephone circuits and ground in any location outside the area affected by the power system ground.

Since all metallic structures in the power house are thoroughly bonded to the same ground; no potential will exist between telephone equipment and other metallic structures in the power house unless the telephone be connected metallically to a circuit extending outside the area within which a considerable difference in ground potential is caused by the fault.

Due to the extensive grounding system, consisting of ground plates, water pipes, the steel reinforcement of the dam itself, and numerous other metallic structures in the power plant, the most practical method of avoiding interruptions to service coincident with failures on the power line seemed to be, in this case, to isolate the portions of the long circuits within the area in which potentials considerably different from outside points might be expected.

Tests were made jointly by the power and telephone interests to determine the impedance of the power system ground connection and the extent of the area which might be at potentials substantially different from those at distant points. These tests were made by feeding current through a ground established at some distance from the power station back to the power station ground and measuring the difference in potential between the power station ground and the telephone central office grounds at Darlington and Belair, Maryland, as well as at intermediate points. These tests indicated that the impedance of the power system ground was at that time between 4/10 and 5/10 of an ohm and that the potentials of points along the west bank of the river and in the Stone and Webster company's construction camp close to the dam varied only about three per cent from the potentials impressed on the power station ground. It was also found that the potential of the water system in the power company's village about 3000 ft. from the dam was only about 6 per cent lower than the potential at the dam and that the potential at points in the village about 100 ft. away from the nearest water pipes was only about 15 per cent different from the potential at the power plant. Further measurements indicated that the earth potential gradient along the telephone line toward Darlington central office was quite gradual and a slight rise in potential was noted even at the Darlington central office, more than two miles from the dam.

A point about a mile away from the dam at the edge of the power company's property where the circuits to the private branch exchange leave the telephone company's line was selected as the most practicable location for insulating transformers to be used in isolating the telephone plant in the area within which substantial rise in ground potential might be expected. The measurements indicated that about 65 per cent of the total drop in potential occurred between this point and the power station ground.

Western Electric Company's No. 50-A repeating coils, insulated between windings for 25,000 volts, have been installed at this point, with lightning arresters on both sides of these coils. The breakdown voltage of these arresters is such that they will not be operated by any rises which it is expected may occur in the potential of the power station ground.

### CONCLUSION

As indicated above, the proper functioning of a power plant and distribution system depends to a considerable extent upon the provision of an adequate communication system by means of which the operating forces can promptly and easily communicate with each other.

In many cases the provision of such a communication system requires the solution of numerous special problems and these are illustrated in this paper by the special problems involved in the design of the communication system of the Conowingo project.

Cooperative consideration by power and telephone engineers of all the available means of communication at an early stage in planning the project, and the adoption of the means most suitable in the specific case should result in the provision of a communication plant of the greatest effectiveness in the operation of the power system.

## Discussion

**E. C. Markley:** It is particularly interesting to note the rather extensive internal communication facilities provided at various points around the building and switch structure. In this connection, is it possible to connect any one of the telephone instruments to the trunk line connected to the Philadelphia load-dispatching system?

As regards dispatching communication, Conowingo is particularly fortunate in its location. It is in an area unusually well provided with underground telephone circuits and therefore only relatively short distances of open-air telephone lines need be protected against storm conditions.

In other parts of the country, an entirely different problem is encountered. Where wire telephony is employed in connection with the operation of 220-kv. and other high-voltage lines, underground cable construction is rather prohibitive and therefore communication must be carried on by open-wire telephone lines. Even in those areas where cable circuits may be used to an extent comparable to this section, hydroelectric stations are usually remote from the centers of the cable telephone system. Power companies have therefore resorted to employing their own telephone lines, carrier current, or space radio. These alternatives were mentioned in the paper, but further discussion along those lines might be of interest, as well as such systems as straight telegraph and printing telegraph systems.

**W. B. Beals:** In regard to the question of the load-dispatcher's circuit being available to communicate with any part of the plant: at the present time the regular load-dispatching circuit is terminated in a telephone, on the station operator's desk, that puts him in direct touch with the load dispatcher's switchboard in Philadelphia. I mentioned a second circuit which has been installed over another route, which is available for what might be called miscellaneous business, general telephone business, or any business that can best be handled by telephone. That line is connected between the regular board of the private-branch exchange—not the load-dispatcher's board—of the Philadelphia Electric Company in Philadelphia and the private-branch exchange at Conowingo. That circuit is available for communication with any of the stations located in various parts of the plant. Furthermore it can be taken over by the load dispatcher and used as an emergency circuit in case of interruption on the regular load-dispatching circuit.

In regard to the telegraph, I think I mentioned that one of the factors that led to the use of telephone facilities was the fact that the Philadelphia Electric Company now has a rather extensive telephone load-dispatching system, and to apply that method of communication to tie-in Conowingo meant simply an extension of the existing system. The printing telegraph, of course, is of very great importance and convenience in case it is desired to keep a record of all orders issued.

**E. B. Tuttle:** In laying out the communication system, this entire interconnection was carefully studied so that any communication circuits which were set up in connection with the Conowingo-Plymouth Meeting part of the system, would be properly coordinated with future possible extensions. That, I think, is one of the particular advantages of making such a communication study very thoroughly in the preparation of the plans for a power system. I should like to add my word to the thought that the power company engineers are fully conversant with their requirements, with what their system needs in the way of power transmission, and also with their needs for communication to a very large extent. Communication engineers, on the other hand, should be in a better position to design what communication facilities are required, particularly if these involve rather extensive interconnection circuits, and so it is particularly fortunate that in connection with this Conowingo job the communication engineers were able at so early a date to assist in the preparation of the system. This is going to be particularly true in the future and even today because of the large increase in the extent of the power system interconnection service. Load dispatching in the East which today may cover 50 miles from a single load dispatcher who would control perhaps all of the system will extend in the course of a few years to hundreds of miles. So it will be of particular advantage to both power and communication companies for communication engineers to be consulted in connection with communication requirements.

The thought was expressed by Mr. Markley that the Conowingo Project was particularly fortunate in its location close to underground communication cables. It may be of interest to note that in setting up the entire project for this intercommunication system about 400 miles of communication circuits appeared to be necessary, and of that not more than 50 miles is in territory where open-wire construction is necessary. The aerial cable as well as the underground cable plant of communication systems are being extended with very great rapidity. During a discussion of this subject with some communication men in Ohio the thought was expressed that the power companies in Ohio did not perhaps feel the necessity for instantaneous communication as did the power companies in Philadelphia, and I could not help expressing the thought that although that might be so at the present time it would not be for long, but that the communication companies might grow in stormproof facilities, about as rapidly as stormproof facilities are demanded. I may be a little optimistic on that subject, however.

In this particular interconnection study, there is one section of 25 miles of open wire required in order to reach the power house, and it is proposed to make that open-wire line of such a strength as will stand any sleet storm recorded to date. The price is not excessive either when constructed on a power line or a communication line.

Mr. Markley expressed an interest in the application of carrier current in connection with load-dispatching systems. The use of carrier current on power lines is a question of economies and continuity of service. Those two points are the prime reasons. It has been pointed out in the papers that when additional emergency service is desired, carrier current may furnish that service. Certain costs in the way of depreciation, interest on the money invested, maintenance, and operation must be taken into consideration, and in the case of the Conowingo-Philadelphia route these amount to very much more than the the annual expense of a leased communication service; and ample facilities were available for emergency routes.

Short-wave radio may also provide, in a similar way, for such continuity of service. At the present time there is extremely little known of the operations of short-wave radio over land for distances under two and three thousand miles. We know, from experiments and studies that have been made, what can be expected of short-wave radio over long distances such as those and for short distances over water, but no experiments of any considerable amount have ever been carried on over land for short distances. We do not know what the effects of electric storms will be, particularly in this part of the country,—and Philadelphia, I believe, is nearly the worst electric storm area we have in the United States. For that reason all you can say for space radio at the present time is that it is experimental. In the course of a few years, additional information will be available and definite recommendations can be made.

Mr. Beals referred to the use of printing telegraph and that brings a very interesting thought to my mind, something on which the communication companies would like to hear some discussion at some time, and that is, what relation does the usage of load-dispatching circuits have to the necessity for printer telegraph or some other recording device. For instance, where the load dispatcher's circuit is assigned exclusively to load-dispatching purposes, as is the case with the Philadelphia Electric Company, there seems to be no desire on the part of the electric company at the present time, at least, for records of the orders passed. Certain other power companies who have their load-dispatching circuits used also for the transmitting of general routine business seem to find it desirable to have a permanent record of all orders passed for load-dispatching purposes. Whether there is any relation between these two facts, I do not know, but I should like to hear some discussion along that line.

**R. A. Hentz:** I can only reiterate what Mr. Beals and Mr. Tuttle have said about the load dispatcher's telephones. The importance of reliable communication is so great that the best was desired—and the cost was not excessive. While we are experimenting with short-wave radio, the results to date have not been reliable enough for this service.

**C. A. Allner:** Referring briefly to the last point mentioned by Mr. Tuttle, both can be suitably combined by hooking up a dictaphone to the telephone as has been the practise on the Pennsylvania-Baltimore System for over ten years.

**E. B. Tuttle:** That has been done in some cases, but engineers who have been working with it find that while certain features are very satisfactory, there are certain other features which are not, due to the load dispatcher's having to change records in the middle of his conversation.

# Quantitative Mechanical Analysis of Power System Transient Disturbances

BY R. C. BERGVALL[1] and P. H. ROBINSON[1]
Associate, A. I. E. E. — Non-Member.

***Synopsis.***—*The quality of service that can be rendered during unavoidable system transients produced by short circuits must be given careful consideration in the analysis of proposed interconnection and transmission projects. An analysis of present systems that have grown until such limitations have apparently been reached, will frequently reveal comparatively inexpensive changes in equipment or operating practise which will permit good service to be given and defer large investments in additional lines for a considerable period.*

*The fundamental mathematical methods for calculating system transients have been presented by other writers during the last few years. These mathematical calculations are of necessity quite involved and consequently can only be applied to very simple power systems. The calculations must be made by thoroughly experienced engineers and the results are not readily understood by the operating staff.*

*In the May 1926 issue of the Electric Journal, under the title "A Mechanical Analogy to the Problem of Transmission Stability," Mr. S. B. Griscom proposed the use of an accurate equivalent mechanical analogy to the electrical system provided perfect springs for representing line reactance could be obtained. A simple mechanical model for qualitatively illustrating the fundamental principles has been demonstrated before various local A. I. E. E. sections and has resulted in a wide general knowledge of the transient behavior of power systems.*

*The present paper covers the adaptation of the mechanical model principles to obtain reasonably accurate quantitative records of transients to be expected on the 220-kv. interconnection between the Philadelphia Electric Co., Pennsylvania Power & Light Co., and the Public Service Electric & Gas Co. These records are obtained by taking motion pictures of the equivalent mechanical system. Resistance or reactance short circuits on transmission lines are duplicated mechanically by applying forces of the proper magnitude and direction to the spring representing the line in trouble, and clearing this spring at each end by blowing fusible links from relays timed to represent the circuit breaker operations on the electrical system. The resulting mechanical oscillations will correspond to those of the electrical system because the inertias, spring characteristics, and torques of the mechanical model elements have been proportioned to the corresponding elements in the electrical system; namely, stored energy, reactance, and kilowatts. The inherent limitation due to imperfect springs has been overcome sufficiently to give results that are accurate within practical limits.*

*It will be shown that the actual setting up of a system on the mechanical model is comparatively simple, and does not require a great deal of experience or mathematical skill. Slow motion pictures of the disturbance can be taken with amateur cameras that are available on the market, and curves of the oscillations plotted from the projection on a screen. The slow motion pictures can be used also for acquainting the operating staff with the effect of various types of disturbances on the system, and for determining the most advantageous sequence of relay operations.*

## FUNDAMENTAL PRINCIPLES OF THE MECHANICAL ANALOGY TO THE ELECTRICAL SYSTEM

THE analogy between the various parts of the electrical system and the equivalent mechanical system are shown in Fig. 1, which represents single generator and its load tied together by the system reactance. The model consists of a generator element and a motor element, mounted on ball bearings and free to rotate independent of each other. For the present, the fault element should be neglected. The rotors have inertia proportional to the stored energy in the generators and loads which they represent. Each element is balanced, and when free from the system and the torque representing generator input or load, is in a state of equilibrium in any position. The weight (a) produces a torque, tending to rotate the generator element in a counterclockwise direction, and the weight (b) produces an equal torque, tending to rotate the motor element in the opposite direction. At synchronous speed, the input kilowatts (torque *a*) to the generator are exactly equal to the output kilowatts (torque *b*) at the load, and the model will be stationary. For any disturbance which suddenly increases the kilowatt load on the system without the governors having time to make a corresponding increase in the generator input, the model will rotate in a clockwise direction, indicating a decrease in frequency. The unbalanced torque (kw. loss in fault) must be absorbed by the inertia of the system and on the mechanical model, will produce oscillations between the relative positions of the two arms similar to the oscillations between the two ends of the electrical system.

With fixed internal voltages in the synchronous machines at the two ends of the system, the phase angle between these voltages plotted against power transmitted is a sine curve similar to Fig. 2 for a purely reactive tie between the ends of the system. The ratio of resistance to reactance of most systems is so small that the resistance may be neglected in making transient analysis without excessive error. The system having power-angle characteristics as in Fig. 2 will pull out of step if the load is gradually increased until the angle between the ends of the system is 90 deg. This is known as the steady-state pull-out limit. When the power being transmitted corresponds to point *a* in Fig. 2, a system disturbance that does not cause the angle to increase beyond point *b* will not cause pull-out.

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[1] Both General Engineers, Westinghouse Elec. and Mfg. Co., East Pittsburgh, Pa.

*Presented at the Regional Meeting of District No. 2 of the A. I. E. E., April 17-19, 1928, at Baltimore, Md.*

It is, therefore, possible to have angular swings between the ends of a simple two-element system that considerably exceed 90 deg. without loss of synchronism. It should be noted that a change in the internal voltages of the machines in the electrical system, or a corresponding change in the lengths of the arms on the mechanical system, will modify the power-angle characteristics of the system.

## CONVERSION OF ELECTRICAL SYSTEM INTO MECHANICAL EQUIVALENT

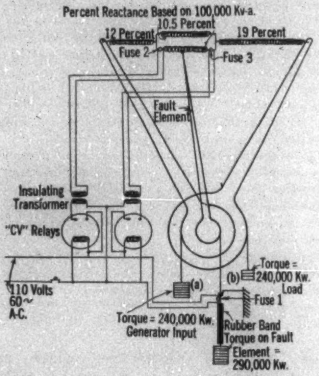
Percent Reactance Based on 100,000 Kv-a.
10.5 Percent
12 Percent
19 Percent
Fuse 2
Fuse 3
Fault Element
Insulating Transformer
"CV" Relays
110 Volts 60~ A-C.
(a)
(b)
Torque = 240,000 Kw. Load
Fuse 1
Torque = 240,000 Kw. Generator Input
Rubber Band
Torque on Fault Element = 290,000 Kw.

FIG. 1

| | Mechanical Analogy | | Transmission System |
|---|---|---|---|
| 1. | Stiffness of spring. | 1. | Reactance represented. |
| 2. | Length of spring. | 2. | Voltage drop across reactance represented by spring. It is proportional to line current. |
| 3. | Counterclockwise torque applied by weight to any element | 3. | Represents kilowatts generator input to system at that point on system. |
| 4. | Clockwise torque applied by weight to any element. | 4. | Represents kilowatts load taken from system at that point. |
| 5. | Radial distance from pivot to any point on spring. | 5. | Line voltage at corresponding point. |
| 6. | Product of length of arm and component of spring tension along radius. | 6. | Reactive Kv-a. |
| 7. | Angle between any two points on the spring. | 7. | Electrical phase displacement of voltages at corresponding points of the system. |
| 8. | Inertia of any element. | 8. | Stored energy at synchronous speed in machines constituting corresponding element of electrical system. |

The first step is to determine the characteristics of the springs which are to represent reactance. The springs should be chosen so that they will not be stretched beyond their elastic limit when the model pulls out. Under this condition, it is desirable to work the springs as close as possible to their elastic limit so that the initial length will be a minimum. Consider that it is desired to select a spring of 10 per cent reactance on a 100,000-kv-a. base. In the electrical system, the 10 per cent on the 100,000-kv-a. reactance tie with 100 per cent voltage at each end, will correspond to a steady-state pull-out limit of

$$\frac{100 \text{ per cent}}{10 \text{ per cent}} \times 100{,}000 = 1{,}000{,}000 \text{ kw.} \qquad (1)$$

The corresponding pull-out torque $T$ of the mechanical model should then be obtained by gradually adding equal weights to the generator and load elements until the steady-state pull-out at 90 deg. between arms is obtained with the spring which is to represent 10 per cent reactance connected to each arm $L$ inches (representing 100 per cent system voltage) from the pivot. This torque $T$ (in ounce-inches) is then equivalent to 1,000,000 kw. on the electrical system.

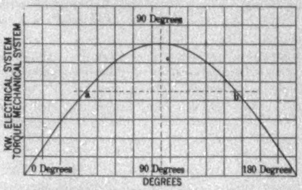

FIG. 2—ANGLE BETWEEN $E_r$ AND $E_s$ IN ELECTRICAL SYSTEM ANGLE BETWEEN GENERATOR AND MOTOR ARMS IN MECHANICAL SYSTEM

The springs representing the reactances of the other parts of the system are then proportioned, taking the above spring as a base. Under the pull-out condition, the force in the spring is $\frac{1.41\ T}{L}$ ounces. This force elongates the 10 per cent reactance spring to 1.41 $L$ in., or would elongate a 1 per cent reactance spring to 0.141 $L$ in. A one per cent reactance spring then can be determined by the fact that it assumes a length of $0.141\ L \div \frac{1.41\ T}{L} = \frac{L^2}{10\ T}$ in. when a weight of one ounce is hung on it. Now the springs to represent the various reactances of a system can be cut to proper length by hanging on them a one-ounce weight,

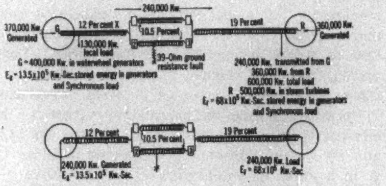
240,000 Kw.
370,000 Kw. Generated
G
12 Percent X
10.5 Percent
19 Percent
R
360,000 Kw. Generated
130,000 Kw. local load
39-Ohm ground resistance fault
G = 400,000 Kw. in waterwheel generators
$E_g$ = 13.5 x 10$^5$ Kw.-Sec. stored energy in generators and Synchronous load
240,000 Kw. transmitted from G
360,000 Kw. from R
600,000 Kw. total load
R 500,000 Kw. in steam turbines
$E_r$ = 68 x 10$^5$ Kw.-Sec. stored energy in generators and Synchronous load
12 Percent
10.5 Percent
19 Percent
240,000 Kw. Generated
$E_g$ = 13.5 x 10$^5$ Kw.-Sec.
240,000 Kw. Load
$E_r$ = 68 x 10$^5$ Kw.-Sec.

FIG. 3—(SEE FIG. 1 FOR SET-UP ON MECHANICAL MODEL)

(or a fraction thereof, if it is found necessary to use a lesser weight). For example, a five per cent spring should reach a length five times that of the one per cent spring with the same weight applied.

The errors due to springs having a finite initial length can be eliminated through the working zone by winding the springs so that there will be an initial compression between turns. As shown in Fig. 4, the relation between spring length and force is then a straight line beyond the finite length of the spring and if projected, this line would start from zero. In the actual operation of the model, the springs are generally stretched beyond the initial length and therefore have such characteristic that no appreciable error is introduced.

The stored energy in a synchronous machine =

$$E = \frac{2.3\,(W\,R^2)\,(\text{rev. per min.})^2}{10^7} \text{ kw.-seconds at synchronous speed.}$$

($W\,R^2$ is in pounds-feet squared) (2)

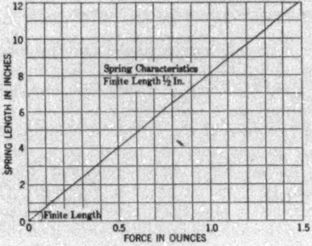

Fig. 4

The total stored energy $E$ at synchronous speed in the machines constituting any particular element of the system may be converted into inertia of the corresponding mechanical model elment as follows:

$$W_1\,r_1^2 = \frac{E \times T \times 2.05}{10^6} \text{ ounce-inches squared.}$$

$E$ = Stored energy in synchronous machines in kw. seconds.

$T$ = Ounce-inches of torque on model at steady-state pull-out with 10 per cent reactance spring attached to each arm $L$ inches (equals 100 per cent voltage) from pivot. (3)

After determining the spring constant and the inertia in the foregoing manner, it can readily be shown that the natural period of any given element of the electrical system and the corresponding element of the mechanical system are identical. Consider the case of a generator having $E$ kw. seconds of stored energy at synchronous speed connected to a system of infinite capacity through 10 per cent reactance on a 100,000-kv-a. base. With 100 per cent internal voltage in the generator, the pull-out of this system will be 1,000,000 kw., as previously shown. The kw. required to produce one electrical degree of displacement when the system is carrying enough load to have a 45-deg. angle then will be

$$p_1 = \frac{1{,}000{,}000 \cos 45}{57.3} = 12{,}300 \text{ kw. per electrical degree.} \quad (4)$$

The natural period of the electrical system at this point then is

$$P = 148.6 \sqrt{\frac{E}{p_1 \times f \times 10^5}} \text{ seconds} \quad (5)$$

$f$ = 60 cycles

Substituting values for $p_1$ and $f$ in (5)

$$P = 148.6 \sqrt{\frac{E}{12{,}300 \times 60 \times 10^5}} \quad (6)$$

$$P = 54.3 \times 10^{-5} \sqrt{E} \text{ seconds} \quad (7)$$

In the equivalent mechanical system the torque at pull-out equals $T$ ounce-inches. The torque per mechanical degree of displacement from the 45-deg. position will be

$$T_1 = \frac{T \cos 45 \text{ deg.}}{57.3} = 0.01234\,T \text{ oz.-in. per deg.} \quad (8)$$

The natural period of the equivalent mechanical system from the torsional pendulum formula is then

$$P = 0.0422 \sqrt{\frac{W_1\ r_1^2}{T_1}} \text{ seconds} \quad (9)$$

Substituting for $W_1\,r_1^2$ its value from equation (3) and for $T_1$ its value from (8)

$$P = 0.0422 \sqrt{\frac{E \times T \times 2.05}{10^6 \times 0.01234\,T}} \quad (10)$$

$$= 54.3 \text{ by } 10^{-5}\,E \text{ seconds} \quad (11)$$

From a comparison of (7) and (11), the natural period of the equivalent mechanical system is identical with that of the electrical system.

The above discussion applies directly to all conditions imposing symmetrical loads on the different phases. For fault conditions, the electrical load may be unsymmetrical; *e. g.*, the fault usually is from one-phase wire to ground. From the stability standpoint, however, a single-phase fault on a polyphase system may be represented accurately by an equivalent symmetrical shunt impedance across the three phases at the point of fault. This was demonstrated by Messrs. Evans and Wagner in their paper *Studies of Transmission Stability*, Appendix III, presented at the Midwinter Convention of the A. I. E. E. Feb. 8-11, 1926.

## COMPARISON OF CALCULATED VS. MECHANICAL MODEL TEST RESULTS ON TWO-ELEMENT SYSTEM

Fig. 3-A shows two generating stations, each supplying some local load and tied together by two transmission lines. Station *G* has a total of 400,000 kw. in waterwheel generators on the line supplying a local load of 130,000 kw. and transmitting 240,000 kw. towards station *R*. Station *R* has 500,000 kw. in the steam turbines on the line carrying a load of 360,000 kw. The remaining 240,000 kw. of the local load being obtained over the transmission system. The stored energy of the synchronous machinery at station *G*, calculated for each item of equipment in accordance with formula (**2**) total 13.5 by $10^5$ kw. seconds. Likewise at station *R* the total is 68 by $10^5$ kw. seconds.

In setting up a complicated system the number of elements must necessarily be kept down to a minimum in order to reduce the possibility of interference between springs. It is desirable, therefore, to combine the inertia of the local load with that of the local generating station into a single element on the mechanical model. Except for the phase angle which it produces in the generator, the local load has no effect on the over-all phase angles of the system. The simplified system used in setting up the mechanical model and calculating the curves which follow is shown in Fig. 3-B. By combining the load with the generator element, the system has been simplified to only two elements on the mechanical model. Disturbances on such a comparatively simple system can readily be calculated by a point-by-point method for comparison with the test results from the mechanical model.

In setting up the mechanical model, the various springs were proportioned to the reactances of the sections they represent, in accordance with the methods previously outlined. The torque equivalent to the 240,000-kw. load being transmitted was applied to the generator and motor elements tending to turn them in opposite directions, thereby holding the system in equilibrium. The inertia of each element of the mechanical model was proportioned to the stored energy of the corresponding element of the electrical system in accordance with (**3**), thereby making the natural period of the mechanical system identical with that of the electrical system.

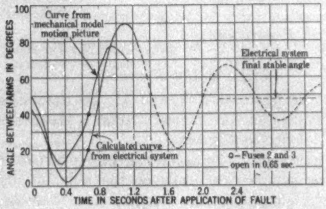

Fig. 5—Comparison of Calculated and Test Curves

For 290,000-kw. line to ground fault on the system shown by Fig. 3A

Fig. 1 shows the mechanical model set-up of the above system. The fault has been assumed to be single-phase line-to-ground, with 39 ohms resistance in the ground circuit. Based on the internal voltages in the machine being practically maintained by means of quick response excitation, the loss in the fault amounts to about 290,000 kw. This is based on internal machine voltages being somewhat higher than the actual transmission voltage, and these higher voltages were also used on the arms of the mechanical model. The power in the fault was converted into equivalent ounce-inches of torque on the mechanical model, and this torque was suddenly applied to the transmission line on which the fault occurred by means of a very light rotating "fault arm" mounted on a ball bearing as shown in Fig. 1. Here the two ends of the spring representing the line in trouble are tied into the remainder of the system through fusible links which represent the circuit breakers at each end of line 2-3 (Fig. 3-B). The *C V* relays are timed to blow these fuses in the same sequence as the circuit breakers would clear the fault on the actual system. It is not necessary to blow the fuses simultaneously. For example, if fuse No. 2 is blown first, the fault arm immediately swings clockwise and continues to apply the fault through fuse No. 3 and the section of spring representing the reactance of this section of the line. The fuses are blown through insulating transformers so that the current can be kept out of the springs. When fuse No. 3 blows, the fault is entirely removed from the system and the fault arm swings clear with spring 2-3 attached to it, thus removing the unbalanced torque which tends to rotate the model, and indicating a decrease in system frequency. If the disturbance is not sufficiently severe to cause pull-out, the system will oscillate and finally assume a new stable angle corresponding to that when transmitting 240,000 kw., with only one line in service.

Fig. 6—Extracts from Motion Pictures of 290,000-Kw. Fault on System by Figs. 1 and 3

a. Mount after fuse No. 1 (Fig. 1) is blown, releasing fault arm.

b. 0.25 sec. after fault. Note the decrease in angle.

c. 0.60 sec. after fault. Fuses No. 2 and 3 (Fig. 1) beginning to clear the spring which is attached to the fault arm.

d. 0.75 sec. after fault. Fault arm with spring 2-3 attached to it, has been cleared from the system.

For curves plotted from the motion picture record, see Fig. 5

By referring to the schematic diagram in Fig. 1, it can be seen that the fault is applied by releasing the weight attached to the fault arm through the blowing of fuse No. 1 immediately after the pushbutton is closed. The closing of this pushbutton also starts the *C V* relays so as to blow fuses No. 2 and No. 3 in the proper sequence.

The weight was attached to the fault arm through a long rubber band, so that no time would be lost in accelerating the mass of the weight applied to the fault arm. The radius of the hub of the fault arm is so small that the rubber band will have linear characteristics, even with a considerable change in the angle of the fault arm.

In some cases where the fault resistance is low, the positive sequence voltage, which is the voltage represented on the model, will dip to about 67 per cent of normal at the point of fault. In such cases an additional spring was used at the top of the fault arm and released simultaneously with the fault arm, so that the positive sequence voltage would be pulled down to this value.

Fig. 6 shows extracts from the motion picture film of the mechanical model with the equivalent of a 290,000-kw. line-to-ground fault applied to the system shown in Fig. 3-A.

Fig. 5 shows the angle between the generator and motor internal voltages at each instant from the time that the fault is applied. The curve taken from the motion picture of the mechanical model is plotted for comparison with the curve calculated from the electrical quantities of the system by a point by point method. There is a fairly close coincidence between the curves, particularly at the extreme angular over travel after the breaker opened. The mechanical model curve has a certain amount of damping, whereas the solid portion of the calculated curve has no allowance for damping which would actually be present on the electrical system. This particular disturbance shows the mechanical model in the least favorable light, since the high kw. loss in the fault is accompanied by only a small reduction in the positive sequence voltage and causes the comparatively light generator arm to swing toward the motor arm so that the finite length of the spring came into action. The finite length of spring coupled with no allowance for damping in the calculation of the electrical system is responsible for the difference between the minimum values of angle in the two curves.

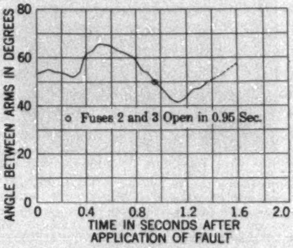

FIG. 7—140,000-KW.—10 OHM LINE TO GROUND FAULT ON THE SYSTEM SHOWN BY FIG. 3A

The fault load must be supplied from the stored energy in the synchronous equipment on the system, causing a decrease in speed, because the disturbance is over in such a short time that ordinary governors cannot come into play. It should be noted that the synchronous equipment at *G* has considerably less stored energy than that at R. Because of the lesser stored energy at *G*, the torque of the fault tends to slow the generator down faster than the load end of the system *R*; therefore for the first four-tenths of a second, there is actually a decrease in the angle. Both breakers (fuses) were assumed to clear simultaneously in 0.65 sec. This is exactly simulated on the mechanical system by blowing the fusible links No. 2 and No. 3 in 0.65 sec. It should be noted that the breaker cleared at a point where the angle was considerably less than the final stable angle, with one section of line out so that considerable over-shooting resulted. The dotted section of the calculated curve shows an assumed decrement leading toward the final stable angle. It should be noted also that when the fault was first applied, a slight discrepancy existed between the calculated electrical angle and the actual angle on the mechanical model.

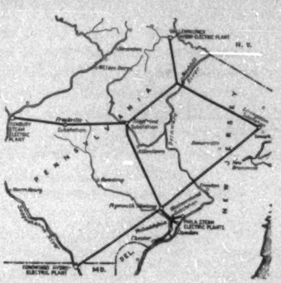

FIG. 8—TERRITORY IN PENNSYLVANIA AND NEW JERSEY TO BE SERVED BY 220-KV. INTERCONNECTED LINES

Fig. 7 represents the 10-ohm low-resistance fault on the system shown by Fig. 3-A, with about 140,000 kw. dissipated in the ground circuit. The positive sequence voltage at point of fault was depressed by means of an auxiliary spring, as previously described, to about 73 per cent of normal at the instant the fault was applied. This depression of the position sequence voltage weakened the tie between the two elements so that the angular displacement between the two actually increased during the first part of the fault, which contrasts with Fig. 5 where the positive sequence voltage was fairly well maintained on account of the high resistance in the fault. The circuit breakers (fuses) cleared the line in trouble at both ends in 0.95 seconds. At this time, the arms were traveling toward each other, and there was some overshooting down to the minimum angle occurring at 1.13 sec. before the arms started traveling apart toward their new positions, with one line out of service.

## Mechanical Model Set-Up of Interconnected System

Fig. 9 shows the 220-kv. interconnection between the Philadelphia Electric Co., Pennsylvania Power & Light Co., and the Public Service Electric & Gas Co. reduced to a simple form for setting up on the mechanical model in the same manner as Fig. 3-B was obtained from Fig. 3-A. This figure shows one of the probable future load conditions. The loads supplied local to each generating station are not shown, as they produce very little effect on the phase angular relations of the interconnected system. Only the transmitted power is shown. As previously outlined, the stored energy and reactance of all of the connected generators were included even though under normal conditions these generators may contribute a slight amount of power to the interconnection. During transient disturbances their stored energy and reactance comes into effect and must be considered.

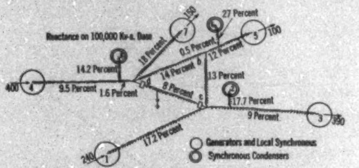

FIG. 9—ARROWS INDICATE THOUSANDS OF KW. ENTERING AND LEAVING NETWORK

Stored Energy of Each Element in Kw-Sec.

1. Conowingo 7.56 × $10^5$
2. Plymouth Meeting 2.2 × $10^5$
3. Phil. Elec. Co., 32.5 × $10^5$
4. P. P. & L. Sunbury 78.0 × $10^5$
5. Public Service Co. 91.0 × $10^5$
6. Livingstone 1.5 × $10^5$
7. Frackville & Siegfried 66 kv. load 39 × $10^5$
8. Siegfried & Frackville Condensers 4.1 × $10^5$

Springs were chosen to represent properly the reactance of each element of the system. The torque required to represent the power generated or the power taken out of the system at each element was determined, and the proper weight to be suspended from each element calculated. In attaching the springs to the arm, allowances were made for the calculated internal voltages. The inertias of the various elements were properly proportioned by hanging equal masses across the elements that required additional inertia. For convenience, these masses were made of tubes that could be loaded with shot. Figs. 10 and 11 show the Fig. 9 system as actually set up on the mechanical model.

With the load and springs properly proportioned, the phase angles between the various component parts of the system assume their proper relationships automatically. The phase angles shown in Fig. 11 correspond very closely to the calculated values. For the set-up shown, the load conditions were such that practically no power was being transmitted over the section of the triangle *B-C* in Fig. 9. Fig. 10 shows this to be true. It can readily be seen that a fault on line *A-C* will be the most severe condition, since the power must be transmitted over the single lines *A-B* and *B-C* after the faulty section *A-C* is tripped out.

Some lines in Fig. 10 utilize two springs in parallel because a single spring of the proper characteristics was not available.

## Analysis of Fault on Line *A-B* Fig. 9 from Motion Picture Record of Equivalent Mechanical Model

*Condition No. 1.* A line-to-ground short circuit on line *A-C* near end *A* having resistance equal to the reactance to the point of fault was considered. This gave the maximum possible kw. loss in the fault and amounted to about 450,000 kw. for the system shown. (For a complete discussion of the effect of variable ground resistance refer to an article by Mr. S. B. Griscom entitled "Characteristics of Ground Faults on Three-Phase Systems" in the April 1927 issue of the *Electric Journal.* The torque representing this kw. loss in the fault was applied to the spring by means of the very light rotating fault arm shown in Fig. 13a. The function of this arm can be seen more readily from Fig. 1. The spring representing line *A-C* was attached to the remainder of the system by means of fusible

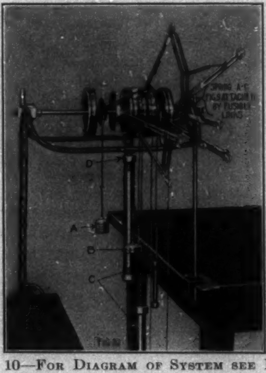

FIG. 10—FOR DIAGRAM OF SYSTEM SEE FIG. 9

A. Weight producing torque tending to rotate element (1) counter-clockwise, representing 120,000 kw. generated.

B. Weight producing torque tending to rotate element (3) clockwise, representing 195,000 kw. load. This weight is at greater radius than (A) accounting for the smaller weight

C. Tubes of equal mass suspended over element (4) to increase its inertia from 32.5 (element alone) to 78 as required by tabulation on Fig. 9

D. Load weights (partly obscured) representing 200,000 kw. being generated by station (4) links arranged to be blown by *C V* relays in order to duplicate the actual opening of the circuit breakers on the system. Fig. 13a shows two successive results at the instant of the application of the fault. The camera shutter did not happen to be open when fuse No. 1 blew, releasing the fault arm, and a spot was placed on the first picture to indicate the blowing of the fuse. The rapid movement of the torque arm is evident, since the pictures are only 0.05 sec. apart.

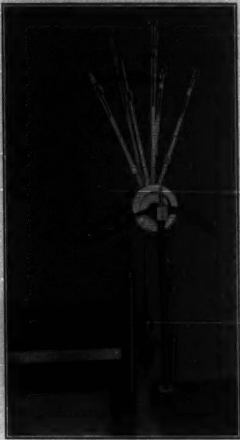

Fig. 11—Front View of Fig. 10

Curve (*d*), Fig. 12, shows the complete angular variation between stations No. 3 and No. 4 and curve (*e*), Fig. 12, shows the corresponding variation between stations No. 1 and No. 3. A cycle counter was included in the field of vision of the motion picture camera as a check on the speed of the film. In Condition No. 1 breakers *A* and *C* cleared the line simultaneously as indicated in Fig. 12. The two successive exposures in Fig. 13b show the released fault arm with the spring *A-C* attached to it swinging clear of the system. In this case the camera shutter did not happen to be open when the fuses representing *A* and *C* cleared.

Fig. 13c shows the crest of the maximum angle between elements 3 and 4. The torque arm with spring *A-B* attached is shown against the stop.

After reaching the maximum angular separation shown in Fig. 12, the stations will oscillate and gradually settle at the new stable position with one line out of service. The present mechanical model does not permit complete rotation and these final oscillations could not be obtained; but they are of no great importance. Fig. 13d shows the final steady-state operating condition with line *A-C* out of service. A considerable increase in the angle between 3 and 4 is evident by comparison with Fig. 13a.

*Condition No. 2.* The magnitude and location of the fault is identical with Condition No. 1, the only change from Condition No. 1 being in the time of operation of the circuit breakers. By referring to Fig. 12, breaker *A* cleared in 0.68 sec. and breaker *C* in 0.93 sec. When breaker *A* opened, the power taken by the fault had to be transmitted over line *A-B* and *B-C* thereby producing a more rapid increase in the angle between the extreme ends of the system shown by Fig. 12. Fig. 14a shows the conditions at the instant fuse No. 1 cleared, releasing the fault arm. The camera shutter happened to be open when this occurred and the flash can be seen in the picture.

Fig. 14b shows the opening of circuit breaker *A* about 0.68 sec. after the torque arm was released. A dot has been placed on the film to represent the flash of the fuse blowing. The location was obtained from a high-speed film taken simultaneously.

Fig. 14c shows the instant that fuse *C* cleared, allowing the torque arm to swing clear of the system with the spring *A-C* attached to it. The flash has been indicated by a dot located from the high-speed film.

Fig. 14d shows the angular swing due to over-travel after the breaker *C* is cleared. The crest of this swing could not be obtained before element 3 hit the stop, but by comparison with a power-angle curve between stations No. 4 and No. 3 constructed in a manner similar to Fig. 2, it can be ascertained that the system would remain in synchronism. The final steady-state condition with line *A-C* out of service will be the same as Fig. 13d. As indicated by the mechanical model, the effect of opening breaker *C* after breaker *A* is somewhat more severe than will actually be experienced in service, because the reactance to the point of fault is

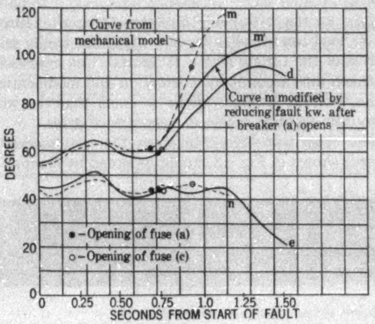

Fig. 12—Condition No. 1

*d* = angle between 3 and 4 (Fig. 9)
*e* = angle between 1 and 3 (Fig. 9)

Condition No. 2

*m* = angle between 3 and 4 (Fig. 9)
*n* = angle between 1 and 3 (Fig. 9)

increased after breaker *A* opens and a corresponding reduction in the kilowatt loss in the fault should have been made. This reduction can readily be calculated and the slope of curve (*m*) Fig. 12 modified by calculation. It would also be possible to arrange to release some of the torque when breaker *A* clears, but this complication can hardly be justified, since the result can be modified readily by calculation. The error due to the torque arm having to swing over sufficiently to take up the initial length of the spring after fuse *A* clears has been found to be very slight due to the small inertia of the torque arm. If desired, this may easily be taken into account by calculation and modifications made, but the change will be so small that the work cannot be justified except in very special cases.

Fig. 13—Condition No. 1
Extracts from Motion Pictures of 450,000-Kw. Fault on System Shown by Fig. 9

a. Conditions at start of fault
b. Fuses (a) and (c) clear practically at the same time
c. Maximum angular swing between 3 and 4
d. Steady state operating condition with line a-c. out of service
For curves plotted from the motion picture record, see Fig. 12

The close coincidence between the two successive records shown in Fig. 12 should be noted by comparing the curves for conditions No. 1 and No. 2 prior to the opening of the fuses.

Fig. 14—Condition No. 2
Extracts from Motion Pictures of 450,000 Kw. Faults on System Shown by Fig. 9

a. Fault applied
b. Fuse (a) opens
c. Fuse (c) opens
d. Maximum angle between 3-4 before element 3 hit the stop
For curves plotted from the motion picture record, see Fig. 12

During the foregoing tests, the application of the force representing the short circuit is made at such an angle that the positive sequence voltage at the point of fault was represented by corresponding depression in the spring. The resistance at the point of fault was equal to the reactance in order to obtain the maximum kw. loss in the fault and this resistance limited the current to such a value that a comparatively small reduction in the positive sequence voltage resulted.

*Condition No. 3.* This condition represents a line-to-ground fault on line *A-C* (Fig. 9) near (*A*) with zero resistance in the fault. The positive sequence voltage at the point of fault will be reduced to about 67 per cent of normal. This was represented by attaching a spring near the end (*A*) which could be released by the blowing of a fusible link to depress the springs representing line reactance to correspond to 67 per cent voltage without applying any torque (kw.) to the system. For convenience, this spring was attached to the fault arm.

Fig. 15 shows the angular change between the extreme ends of the system plotted against time as taken from the motion picture record. Fig. 16a shows the initial condition a moment after the voltage at (*A*) was depressed to about 67 per cent of normal. Fig. 16b shows conditions at the instant the fusible link representing breaker *C*, cleared. The fuse representing breaker *A* failed to clear and Fig. 16c shows the angular relation existing when stations No. 3 and No. 4 were at their extreme angular displacement. With the internal voltages in the generators maintained, the system will not pull out of step even though breaker *A* fails to clear the fault. This may be ascertained from Fig. 15 since the maximum angle of 140 deg. between stations No. 3 and No. 4 did not cause pull-out, and they are swinging back toward a smaller angle. The advantage gained by the use of high-speed excitation, which in so far as practical, maintains the internal voltage in the generators, is evident from an inspection of Fig. 16c.

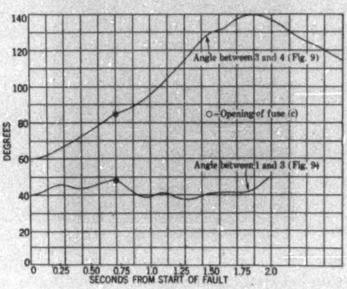

Fig. 15—Condition No. 3—Zero Resistance Line to Neutral Fault Near (a) Fig. 9

## CONCLUSION

This paper describes the initial attempt to make a quantitative analysis of system transients from motion picture records of a mechanical system having constants proportioned to those of the electrical system. The model was built up of existing equipment and proved to be adequate for the solution of a system problem that involved too many elements for handling by means of mathematical calculation. The experience gained with this model will prove of value in the development of a model having a greater degree of flexibility for use in analyzing transient conditions on systems with accuracy limitations comparable with the resistance type calculating board now generally used to determine short-circuit conditions for relay and circuit-breaker applications.

It is possible to add a great many refinements to the mechanical model to represent the reactions taking place on systems during transients which have not been taken into account on the device that has been described. In the authors' opinion, it is preferable to use a simple device because results obtained will be comparable in accuracy with the estimates of system conditions to be investigated, since these estimates generally are concerned with conditions that have been projected considerably into the future. Methods of representing a decrease in the internal voltages of the machines and taking into account line resistance as well as reactance have already been described in the May 1926 issue of the *Electric Journal*.

FIG. 16—CONDITION NO. 3

EXTRACTS FROM MOTION PICTURES OF ZERO RESISTANCE LINE TO NEUTRAL FAULT AT (a) FIG. 9

a. Instant after fault was released, depressing the voltage at (a) to about 66 per cent normal

b. Instant after fuse (c) opened

c. Maximum angular swing between 3 and 4

In the transient conditions analyzed in this paper, the load and the kilowatts of input to the generators were assumed to remain constant during the disturbance. Line-to-neutral short circuits seldom cause the positive sequence voltage to drop below 70 per cent of normal and most induction and synchronous motor loads will stay on the line. The transient is over in such a short time that the governors of the generating units do not have time to change greatly the power input. If, however, it is desired to change these factors, it is readily possible by either electrical or mechanical means to change the torque applied to the various elements during the transient. It is also possible to change the torque representing the kilowatts in the fault at the same time that circuit breakers open and reduce the fault current.

The mechanical analogy can be used for the following purposes:

1. Investigation of the adequacy of proposed transmission systems and interconnections for rendering good commercial service in spite of the transient disturbances that are to be expected.

2. Determination of the characteristics that are to be desired in equipment in order to render the required service.

3. Analysis of the most desirable sequence of relay operation. This factor is of great importance in the successful operation of large transmission systems.

4. The mechanical model should be of value in analyzing disturbances on existing systems that have been recorded with automatic oscillographic instruments. The disturbances as recorded can be repeated on the mechanical system set-up and the transients studied by means of slow motion pictures for the benefit of the operating staff.

The results obtained with the initial mechanical model used for quantitative analysis of system disturbances indicate the possibility of building somewhat more flexible mechanical models and the preparation of simple instructions for setting up systems so that the work can be handled by men who have had no previous experience in the calculation of system transients. The mechanical model can be used for quickly analyzing transients on systems having too many elements to be handled mathematically.

In the development of the mechanical model for quantitatively analyzing system transients, the authors have freely consulted the past work of Messrs. Griscom, Wagner, Evans, and Fortescue. The authors wish to express their appreciation of the energetic assistance with the mechanical work rendered by Mr. R. W. MacKay.

### LIST OF SYMBOLS USED IN THE FORMULAS

$L$ = Length of arm on mechanical model representing 100 per cent voltage.

$T$ = Ounce-inches of torque required to pull out the system with a 10 per cent reactance spring attached to each arm at $L$ inches from the pivot. It is equivalent to the calculated pull-out kilowatts of the identical electrical system.

$W_1 r_1^2$ = Inertia of mechanical model element in ounce-inches squared. $W_1$ is weight of element and arm in ounces (not mass) and $r_1$ is radius of gyration in inches.

$E$ = Stored energy at synchronous speed in the machines at a station measured in kw-sec.

$W R^2$ = Inertia of a synchronous machine rotor in pounds-feet squared. $W$ is the weight of rotor in pounds (not mass) and $R$ is radius of gyration in feet.

Rev.per min. = Revolutions per minute.

$p_1$ = kw. per electrical degree of displacement from normal position.

$P$ = Natural period of electrical or mechanical system in seconds.

$f$ = Frequency in cycles per second.

$T_1$ = Torque in ounce-inches per mechanical degree of displacement from the normal position.

## Appendix

### Derivation of Formulas

*Formula* (**1**). Consider a system having 100 per cent internal voltage maintained at each end and a total reactance of $X$ per cent based on $M$ kv-a. Then:

$$\frac{100 \text{ per cent}}{X \text{ per cent}} M = \text{kw. at pull-out.} \qquad (\mathbf{12})$$

It is well known that pull-out will occur at a 90-deg. angle between the voltages with a pure reactance tie. The reactive line drop then equals 100 per cent $\sqrt{2}$, which corresponds to $\frac{100 \text{ per cent } \sqrt{2}}{X \text{ per cent}} M$ kv-a. being transmitted. Since the phase angle is 45 deg. the kw. at pull-out as given by (**12**) may be obtained by multiplying the kv-a. by cos 45 deg. $= \frac{1}{\sqrt{2}}$.

*Formula* (**2**). This formula has been published by others without any derivation being given. For convenience, it will be derived below.

The standard formula for rotational kinetic energy is:

$$\frac{W\ R^2\ \omega^2}{64.4} \text{ ft.-lb.}$$

($W$ is weight of rotor in pounds)
($R$ is radius of gyration in feet)
($\omega$ is angular velocity in radians per second). (**13**)

Substitute in (**13**) for $\omega$ its value in terms of (rev. per min.):

$$\omega = 2\,\pi \frac{(\text{rev. per min.})}{60} = \frac{\pi\ (\text{rev. per min.})}{30}$$

radians per second. (**14**)

Multiplying by the factor 13,560 $\times 10^{-7}$ to convert ft.-lb. to kw. Second formula (**2**) is obtained.

$$(\mathbf{2})\quad \text{E} = \frac{2.3\ (W\ R^2)\ (\text{rev. per min.})^2}{10^7} \text{ kw-sec.}$$

*Formula* (**3**). Conversion of electrical system stored energy ($E$-kw-sec.) into equivalent $W_1 r_1^2$ (ounce-inches squared) on the mechanical model.

In the paper under "Conversion of the Electrical System into Equivalent Mechanical System" the method of obtaining the proportionality factor between kilowatts in the electrical system and torque in ounce-inches on the mechanical model was described. Consider an element of the electrical system having $E$ kw.-sec. of stored energy at synchronous speed. If a load $\text{kw.}_{po} = T$ oz.-in. on the mechanical model ($\text{kw.}_{po}$ = pull-out kw.) is taken from the synchronous machines constituting $E$, they will slow down a total of $\phi_1$ electrical degrees if no additional power is supplied.

$$\phi_1 = \frac{5400\ (\text{kw.}_{po})}{E}\ t_1^2 \text{ elec. deg.} \qquad (\mathbf{15})$$

This formula will be derived later in the appendix.

The torque $T$ applied to the mechanical system should cause a movement of $\phi_1$ mechanical degrees in $t_1$ seconds if the $W_1 r_1^2$ of the model is properly proportioned to $E$ of the electrical system. For the mechanical system:

$$\phi_1 = \frac{11{,}085\ T}{W_1\, r_1^2}\ t_1^2 \text{ mechanical degrees.} \qquad (\mathbf{16})$$

This formula will be derived later in the appendix.

Equating (**15**) and (**16**) and canceling out $t_1^2$:

$$W_1\, r_1^2 = \frac{E \times T \times 2.05}{\text{kw.}_{po}} \text{ oz.-in. squared.} \qquad (\mathbf{17})$$

In the example shown in the paper $\text{kw.}_{po} = 10^6$ or

$$(\mathbf{3})\quad W_1\, r_1^2 = \frac{E \times T \times 2.05}{10^6} \text{ oz.-in. squared.}$$

In the foregoing, $E$ has been assumed to remain constant during changes of speed. This has been found to be sufficiently accurate for stability calculations because the transients last such a short time that the departure from synchronous speed is very small.

*Formula* (**15**). Used in deriving formula (**3**).

The torque ($T_{36}$ lb.-ft.) that will change the angular velocity of a body having an inertia of $W\,R^2$ (lb.-ft. squared) from $\omega_1$ to $\omega_2$ radians per second in time $t$ seconds as given by the standard formula is:

$$T_{36} = \frac{W\ R^2\ (\omega_1 - \omega_2)}{32.2\, t} \text{ lb.-ft.} \qquad (\mathbf{18})$$

In deriving formula (**16**) it is convenient to consider all machines as running at 3600 rev. per min. and convert the $W\,R^2$ and electrical torque to this base, since the mechanical and electrical degrees are the same at this speed. From formula (**2**).

$$E = \frac{2.3\ (W\ R^2)_{36} \times 3600^2}{10^7} \text{ kw.-sec.} \qquad (\mathbf{19})$$

or $(W\ R^2) = 0.335\ E$ lb.-ft. squared at 3600 rev. per min. to have stored energy of $E$ kw.-sec. (**20**)

The torque ($T_{36}$ ft.-lb.) at 3600 rev. per min. produced by ($\text{kw.}_{po}$) is:

$$\frac{\text{kw.}_{po}}{0.746} = \frac{2 \times 3600 \times T_{36}}{33000} \qquad (\mathbf{21})$$

or

$$T_{36} = 1.95\ \ (\text{kw.}_{po}) \text{ lb.-ft.} \qquad (\mathbf{22})$$

The angular velocities $\omega_1$ and $\omega_2$ in radians per second may be converted to degrees per second as follows:

$$\omega_1 = \frac{\omega_{10}}{57.3} \quad (\mathbf{23}) \qquad \omega_2 = \frac{\omega_{20}}{57.3} \quad (\mathbf{24})$$

$\omega_{10}$ and $\omega_{20}$ are in either electrical degrees per second or mechanical degrees per second on the 3600 rev. per min. base previously referred to.

Substituting (**20**), (**22**), (**23**), and (**24**) in formula (**18**):

$$(\text{kw.}_{pe}) = \frac{E\,(\omega_{10} - \omega_{20})}{10{,}800\,t} \qquad \textbf{(25)}$$

The angular change $\phi_1$ (elec. deg.) in time $t_1$, may be determined as follows:

$$\phi_1 = \int_0^{t_1} (\omega_{10} - \omega_{20})\,dt = \int_0^{t_1} \frac{10{,}800\,(\text{kw.}_{pe})}{E}\,t\,dt \qquad \textbf{(26)}$$

or $$\phi_1 = \frac{5400\,(\text{kw.}_{pe})\,t_1^2}{E}\ \text{elec. deg.} \qquad \textbf{(15)}$$

*Formula* (**16**). Used in deriving formula (**3**). Starting from formula (**18**) as a basis substitute for $T_{36}$ (ft.-lbs.) its equivalent torque $T$ (in.-oz.)

$$T_{36} = \frac{T}{16 \times 12} = \frac{T}{192} \qquad \textbf{(27)}$$

The $W R^2$ (lb.-ft. squared) may be converted into $W_1 r_1^2$ (oz.-in. squared) as follows:

$$W R^2 = \frac{W_1 r_1^2}{16 \times 12 \times 12} = \frac{W_1\ r_1^2}{2304} \qquad \textbf{(28)}$$

Substituting (**23**), (**24**), (**27**), and (**28**) in formula (**18**):

$$T = \frac{W_1 r_1^2\,(\omega_{10} - \omega_{20})}{22{,}170\,t}\ \text{oz.-in.} \qquad \textbf{(28)}$$

($\omega_{10}$ and $\omega_{20}$ in mech. deg.)

The angular change, $\phi_1$ (deg.) in time $t_1$ may be determined as follows:

$$\phi_1 = \int_0^{t_1} (\omega_{30} - \omega_{20})\,dt = \int_0^{t_1} \frac{22{,}170\ T}{W_1 r_1^2}\,dt \qquad \textbf{(29)}$$

or $$\phi_1 = \frac{11{,}085\ T}{W_1 r_1^2}\,t_1^2\ \text{mech. deg.} \qquad \textbf{(16)}$$

## Discussion

**B. Van Ness:** The eastern 220-kv. interconnection presents an unusually interesting problem from the stability standpoint because of the large number of different factors involved. Of particular interest is the proposed parallel operation of existing stations equipped with normal excitation and new stations equipped with quick response and even superexcitation.

In this connection I should like to ask the authors of the papers if their studies have indicated any need for the installation of quick-response excitation in the existing stations in order that the speed of response be more nearly uniform throughout the system; also if voltage fluctuations and surges are to be expected from wattless readjustment caused by the difference in speeds of excitation response.

**L. G. Smith:** There are several points that I am not sure the authors of the paper have considered in designing the mechanism for calculating system stability. One is the effect of steam generating stations in that the steam governors may start to function during the period of oscillation during the transient condition and thus superimpose their effect upon the natural oscillation that may occur. Another point is the time lag of relays which may have some effect upon system stability. The energy supplied to the normal short circuit is almost entirely wattless. Under these conditions we might actually have an unloading effect on the generators and a tendency for them to speed up. This may have some effect upon the stability of the system. Can this effect be determined?

The growth of interconnections has introduced the subject of stability in many of our power systems. In the East it is more or less a practise to interconnect systems through solid interconnections, attempting to hold all parts of the system in synchronism. I understand that there is a tendency on the Pacific Coast to adopt a system of loose linkages, that is, to tie the system together loosely so that various parts will separate in case of trouble. Perhaps Mr. Baum can give some thoughts on this subject.

Quick response excitation would function to hold the voltage up during a short circuit. Suppose that the trouble is cleared and the short circuit removed from the system after the quick-response excitation of the condensers has functioned. Is the system designed to reduce the voltage quickly in order to prevent an over-voltage on the synchronous condensers, which may cause an insulation failure on some part of the system?

**F. G. Baum:** No electrical system can be operated without means for removing defective sections. The solution has been the bother of the electrical engineer for many years.

Thirty years ago generators were often advertised as being very good because they had very large reactance. One manufacturer made it a point that you could actually short circuit his machine for hours at full voltage and it would do no harm. All that was good for the time, but it just happens that that generator manufacturer is not in business now; perhaps he had the wrong idea.

There was a reason, then, for having high generator reactance, because 30 years ago we had no oil switches whatever when we started operating on 40,000 volts, nothing but fuses and air switches. The average interruption at that time was some 25 to 30 min. We made up our minds that this had to be remedied, so we made up some improvised oil switches. With the subsequent improvements in switches and relays, results have been accomplished that are really wonderful. Now we are striving to maintain the generated voltage by high-speed excitation and other means.

That matter of cutting the system into parts, which has been mentioned by one of the speakers, was tried 25 or 30 years ago when we tied the northern end of the Pacific Coast system to the south switch and a man stood at that switch day and night and separated it by pulling a lever. Of course operations are now going forward in an improved way. Some 50 different power plants feeding into the San Francisco Bay District are so connected that in case of trouble they can be divided into parts.

I should like to call attention to the synchronous condenser value. It has, first, a value in increasing the power capacity of a transmission line. That is, a 220-kv. transmission line has a *normal* capacity, as I call it, of transmitting power of about 120,000 kw. at a constant voltage. That is, when that amount of power is being transmitted over a transmission line the charging current is just such as to give a uniform voltage over the transmission line, which could theoretically go around the world and end up with the same voltage you start with.

The charging current of a transmission line is some 25,000 kv-a. per hundred miles. It used to be thought that that was a liability, but if you match that 25,000 charging kv-a. with 25,000 to 30,000 of synchronous-condenser kv-a. you make that charging current an asset.

The second advantage of the condenser is that it increases the stability of the transmission system.

The third value of the condenser is not generally recognized. I will refer to the Pacific Gas & Electric Company system, comprising more than 50 different power plants feeding a general receiver area. Before we had a main synchronous-condenser control station it was necessary for the load despatcher to telephone to 50 different operators as to how much kv-a. they should put into the system at different times of the day. And it became almost impossible to handle that job because one plant would try to slip the charging kv-a. onto the other fellow. At the present time there is 80,000 kv-a. in the central system condenser station feeding into it, and the load despatcher tells the power stations what kilowatts he wants delivered and the voltage regulation is all done by the one condenser station. The load despatcher told me a few years ago that the old system would be practically impossible to operate, but now he has one station which can control the voltage of the whole system as he desires. Now the instructions are simpler and the whole system operates much better and probably a very large system like that would be impossible to operate without synchronous condensers, if they were of value, for no other reason than to simplify the method of operation of voltage regulation.

**F. C. Hanker:** The ultimate aim of any power system is to maintain continuity of service, and these recent modifications are for the purpose of improving the service record. Mr. Baum has mentioned that you have to remove the line or section of the circuit in trouble off the system just as quickly as possible. If you do that within a tenth of a second, or within that order of time, your general problem of operation and maintaining service will be very much simplified.

One of the problems that resulted from the study of system conditions was the method of calculation. These are more involved, sometimes, than the systems themselves and Mr. Bergvall is to be commended on the use he has made of the simple, mechanical model, in simplifying the analysis of the more complicated systems. The simple model has done more to visualize to the operating man the conditions that exist in his system than any other method; far more than could be done by any amount of discussion.

At the last Pacific Coast Convention the operating men, in connection with the manufacturers, presented a paper showing two years of operation on the Edison System. If we had similar data on other systems we could soon set up a definite measuring stick to help tell us where we are going and where we would land on systems of two and three times present capacity. It wont be many years before our systems are going to double and quadruple and when that time comes we are not sure whether the present system of operation will be desirable and effective, or whether we shall have a modified system, which may be either a combination of the present with a new, or perhaps an entirely different one. I think the operating engineers should give more thought to that phase of the matter because it does offer a problem of considerable importance.

**A. E. Bauhan:** Not so many years ago the question of stability was practically unrecognized as a cause of major system troubles. In my experience with the Baltimore systems some years ago, we had numerous cases where ordinary 13,000-volt feeder short circuits were given the blame for major outages. These short circuits in themselves were really minor troubles and should have cleared by relay action without serious interruption of service, but for reasons not clearly understood at the time, general disruption of the whole system with loss of interstation ties and main transmission followed. It was later recognized that with the system connections then in use there was a condition of transient instability which was the real cause of the major trouble. Since then more recognition has been given to this matter generally and with better understanding of the conditions influencing stability under short-circuit conditions, system operation is being improved.

When the particular interconnection referred to in this paper was conceived a few years ago the question was raised as to what the stability limit would be, and the figure mentioned was quite different from the one that has recently been determined. As time went on, and new calculations were made, lower and lower limits were reported. Later the figures from various sources became consistent with each other and there was more assurance that the approximately correct answer had been reached. This is significant of the progress which has been made in determining maximum power flow and the mechanical analog which has been explained here today has had much to do with clarifying this problem.

Fortunately, with regard to the Pennsylvania-New Jersey interconnections, distances are short and the question of stability did not affect the economic feasibility of the project, the stability limits being considerably higher than the loads which were necessary to justify the interconnection. However, on long-distance transmission of large amounts of power, the stability limit affects the number of circuits and the amount of synchronous-condenser capacity and therefore the cost of a major element of the delivered power cost. Its accurate prediction in such cases is of great importance in determining the economy of the project.

With regard to the question as to the effect of voltage dips in one part of the system being transmitted to another part of the system, my view is that we will have some trouble from that source. There will doubtless be a larger number of voltage dips on the individual systems than would have occurred without interconnection. However, I do not regard such voltage disturbances as being important. To the lighting customers they are mere flickers of the lights. To the power customers whose switches are equipped with instantaneous low-voltage releases, the more serious voltage disturbances will cause interruptions. In those applications where continuity is inportant the instantaneous low-voltage release has no place in any event and the remedy lies in seeing that all such applications have time delays on any necessary low-voltage releases.

**P. H. Robinson:** The Westinghouse Electric & Manufacturing Company has conducted extensive tests and development work on the regulating equipment for the condensers being supplied for the Westmoreland Substation. In order to handle the heavy field currents necessary to build up the reactive kv-a. at a high rate of speed, special regulator contactors were developed and will be used in connection with a suitable system of relays for control.

The exciters are of special design, having a laminated frame and comparatively few field turns. Laminating the frame was found necessary in order to reduce the retarding effect of eddy currents on the building up of the flux in the exciter. If a solid frame were used it would not be possible to obtain such an extremely high rate of building up of the exciter voltage.

While we were conducting tests on a synchronous condenser, a phenomenon occurred which was quite interesting. It was found for the particular machine under test that three or four times normal field current would cause hunting and finally make the condenser drop out of synchronism and stop suddenly. This heavy field current made the natural period of the machine identical to a natural oscillation existing in the supply system.

It might be well to investigate the possibility of such an occurrence on an actual system.

**A. F. Bang:** In underground systems in practically all large cities, nowadays, it is recognized as good practise to have reactance coils at both ends of a feeder. These coils not only limit the current that the switches have to take care of, but also, and this is the main point, keep up the voltage on the station busses between which the fault is located.

Now, when almost everybody realizes that this is the right thing to do in city systems, why is it almost standard practise to parallel on the high-tension side when it comes to transmission-line systems? I, for one, cannot see the logic of the situation. By not paralleling the transformers on the high-tension side, the transformers themselves will act as reactance coils to keep up the voltage on the generating station busses. A system of this kind has been used successfully for many years on the Pennsylvania Water & Power Company's 70,000-volt lines and we believe the system has many advantages, particularly for relatively short lines.

**Raymond Bailey:** The studies which have been made on the Coast where 220-kv. systems have been in operation for some time, and also those made in the East largely by engineers of the manufacturing companies, have proved very helpful. Considerable progress certainly has been made, but I believe we still have much to learn about stability of operation, and it is expected that in the future we will profit not only by further analytical studies that will be carried along, but also from actual experience of operation.

It seems to me to be of extreme importance, particularly in a system in which large blocks of power are transferred over great distances, to isolate faulty sections of the system with minimum time delay in order to prevent unstable operation. The development of circuit breakers that open the circuit more quickly or development of relay protective schemes that do not depend upon a time delay in their operation may lead to reduction in the length of time required to clear faults from systems.

Our efforts in designing the relay protective system for the Conowingo project have been to secure means for isolating faulty sections as quickly as possible under all conditions. This condition, along with the high-speed excitation on the Conowingo generators and on the condensers at the receiving end, we believe will do much to insure stability of operation.

**R. C. Bergvall and P. H. Robinson:** Mr. Smith has brought up the question of governor action during system transients. The transients produced by severe short circuits are of such brief duration that normally the governors will not appreciably change the input to the prime movers until after the disturbance has been cleared. A number of cases is known where disturbances and the accompanying switching operations have set up severe hunting between interconnected stations whose governors were not properly adjusted. The solution of this problem is proper governor adjustment and is beyond the scope of the mechanical model analysis. Wattless short circuits that are severe enough to cause the generators to speed up indicate that the short circuits have been of the 3-phase type, entirely removing the tie between the generators and the load and the speeding up indicates that loss of synchronism has occurred. The time lag in the relays has been added to the circuit breaker operating time in making the analysis.

Mr. Bang mentioned using reactors in transmission lines similar to the present practise which has proved beneficial on lower-voltage circuits. Generally, there are only two or three high-voltage transmission lines tying together two systems. With reactors placed in these lines the loss of one circuit greatly increases the amount of reactance through which synchronism must be maintained, and the reactors even though they cushion the initial short circuit will be detrimental due to decreasing the strength of the tie line. On lower-voltage circuits the reactors are generally used in feeders that are not depended upon for furnishing synchronizing power and the reactors are beneficial in reducing the severity of the short circuit.

Mr. Bang brought up the question of using transformers as a part of the line to serve as reactors and limit the short circuits. There are undoubtedly cases where such practise would be of value but it is impossible to give general conclusions as each case would have to be considered individually.

The use of quick-response excitation systems on the important generating stations in an interconnected system will be of great value in maintaining stability during transient disturbances.

**D. M. Jones:** With the mechanical device described by Messrs. Bergvall and Robinson it would appear that once a given system is reduced to an approximate mechanical counterpart it would be very easy to obtain data on the relative effect of variation in certain basic factors; also, in a sense, the analog is free from the small cumulative error inherent in step-by-step calculation processes. Finally, it has a certain visual quality which is of value in providing general images of what takes place on a system during disturbances.

The analog in turn has its inherent difficulties. It is evident that it is devoid of large amounts of friction. It might at first be thought that such friction as might exist would be very closely akin to the damping that actually occurs in the system. Two comments on that might be of interest.

Of course to the small degree that there is any friction it is not an exact counterpart of the damping, as friction is practically a constant force and damping is a force which should vary with the rate of motion of the levers.

The other thing that may be of more interest is that it is a matter of both experience and test that certain system conditions, especially those including high-resistance lines, result in a considerably reduced or even at times an actual negative damping. This condition not only causes mechanical friction to be at basic variance with the true requirements, but also suggests a point of departure between the analog and the facts.

The presence of appreciable series system resistance also results in a condition which is not rigidly represented by the symmetrical simplicity of a generator lever and a load lever crosstied with a spring with the resulting maximum mechanical torque angle of 90 deg.; for such resistance tends to increase the real maximum load angle for the generator and at the same time to decrease it for the load to values departing from the basic value above mentioned.

Also, to the degree that salient-pole machines are present on a system, a condition arises which does not coincide with that assumption of a sine wave torque-angle curve for all machines, on which the analog is based, because salient-pole machine torque-angle curves are never true sine curves and may depart appreciably from them as has been brought out in *Synchronous Machines I*, by R. E. Doherty and C. A. Nickle, (see A. I. E. E. TRANS., Vol. XLV, 1926, p. 942).

Again, although mechanical simplicity suggests the representation of short-circuit disturbances by a fixed lever length to which is applied a fixed force, which is the equivalent of a constant voltage at the short, and a fixed loss therein, the actual voltage and loss are never constant throughout the duration of the short circuit and often vary considerably.

These comments in suggesting certain limitations in the mechanical analog are not offered in condemnation of this most interesting device, but rather to point out the probability that there will be certain system conditions where the results obtained from it will be satisfactory and others where the errors may be unduly large, and to express the hope that work on it may continue to the end that the connection between the type of system condition and the resulting error may be thoroughly established.

Mr. Smith mentioned overvoltage with regard to excessive excitation applied to synchronous condensers. He has mentioned that very justly. That is one of the distinct limitations of excitation to abnormal degrees. In the condenser on the Conowingo system this is taken care of by the regulator, and of course that maximum voltage on the exciter disappears very quickly, so that the amount of excitation that has to be reduced is not a thousand volts but that equivalent refers to the double field current, and as has been pointed out you are up against a condition which is influenced by two factors: how quick your equipment is in controlling the overvoltage, and the degree of overvoltage which the equipment itself would produce on the actual system.

I wish to substantiate the remarks made by Mr. Bergvall about the lightning-arrester question. It was felt that the maximum voltage which the lightning arrester would allow was considerably lower than the voltage which might occur on the line and therefore that its installation was justifiable.

I might make one minor comment with regard to a remark that Mr. Bang made. If, by use of reactance in any position you can materially reduce the disturbance without materially reducing the capacity of the synchronizing path you have done a very good thing. Now on our network it is probable that when you put in reactors you have not materially reduced the synchronizing path in general, as the thing is a pretty widespread network, while the reactor is very effective in reducing the short circuit. Furthermore if you had any system and short circuits of such a nature that you could control the magnitude by putting in reactance in such a way that you didn't influence the synchronizing path, it would be of advantage. That might be one way of obtaining certain benefits in stability. You could limit the path of the fault current probably without limiting the path of the power flow, and that would be of advantage.

**R. C. Bergvall and P. H. Robinson:** With reference to Mr. Jones' discussion, we recognize that friction is not an exact counterpart of damping, but both of these forces are so small that in an analysis of this type they can be neglected. In mots systems of sufficient magnitude to warrant a stability study no appreciable error is introduced by neglecting the series resistance as it amounts only to 1/10 or 1/12 of the reactance. It is true that salient-pole synchronous machines deviate somewhat from the sine-wave torque-angle curve for steady-state conditions, but during transients we are concerned with the characteristics of machines having the internal flux linkages maintained by means of quick-response excitation and the torque-angle characteristics approach the sine function. The demagnetizing action of the fault current in the armature of the synchronous machine is counteracted by the increase of excitation brought about by rapidly increasing the voltage applied to the field of the synchronous machine.

It is recognized that the application of a constant force to represent a fault is not exactly correct as pointed out in the paper. We must consider, however, that for the analysis of a complicated problem of this nature it is necessary to make certain assumptions which although not rigidly true, simplify the problem and do not affect the results to such a marked degree as to cause them to be incorrect in the general case. There is no method of predetermining the variation of the loss in a fault as there are so many factors involved that it would be impossible to exactly duplicate a condition. Any given or assumed fault condition can be analyzed and its effect upon the system determined.

The stability study has indicated the desirability of using quick-response excitation systems on the large generating units to maintain internal voltage under fault conditions. The value of such a scheme has been recognized for some years but only recently has been put into practise.

# Squirrel-Cage Rotors with Split Resistance Rings

BY HANS WEICHSEL[1]
Fellow. A. I. E. E.

*Synopsis.—The characteristics of a squirrel-cage induction motor are investigated when the resistance rings are provided with cuts 360 electrical deg. apart and the cuts in the front ring are displaced against those in the back ring by 180 electrical deg.*

*A theoretical investigation is given, which leads to the conclusion that splitting the rings results in an equivalent ring resistance which varies with double-slip frequency in the ratio of one to three; and the average ring resistance is twice what it was before the rings were cut. The variable rotor resistance effects a periodic fluctuation of the line current and rotor speed. The fluctuations have double-slip frequency. The theoretical conclusions are checked by tests and oscillograms. Test results show that the splitting of the rings is followed by increased rotor leakage, which results in a starting torque smaller than that corresponding to the increased resistance and original leakage.*

* * * * *

WHEN the starting torque of a squirrel-cage induction motor is not sufficiently high, the remedy often suggested is to divide each resistance ring by aid of saw-cuts into half as many sections as there are poles, the saw-cuts in the front ring being displaced against those in the back ring by an angle corresponding to one-pole pitch (180 deg.). A developed view of a four-pole squirrel-cage arranged in this manner is diagrammatically represented in Fig. 1.[2]

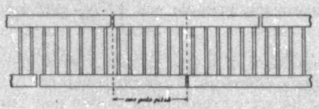

FIG. 1

The squirrel-cage rotor with its rings modified in this manner offers a resistance higher than an identical squirrel-cage with uncut rings. Below, it will be determined how much that part of the squirrel-cage rotor resistance which is due to the rings only is increased by cutting the rings. It will be found that a squirrel-cage with cut rings offers an *average* ring resistance equal to twice the resistance of the original uncut rings. A proof for this is as follows:

First, it is necessary to consider the current distributions and losses which take place in a squirrel-cage of the standard construction, using solid end rings, or so called resistance rings. Fig. 2 represents the current distribution in a two-pole squirrel-cage rotor with solid rings. In drawing the current distribution, it has been assumed that the ampere conductors on the stator follow a sine-law distribution in space. Strictly speaking, such a distribution exists only when the stator has an infinite number of phases and slots; but even for a finite number of phases and slots the above distribution is approached. For a sine-shaped stator ampere-conductor distribution, the rotor-current distribution must also follow the sine law. The rotor ampere-conductor distribution rotates in respect to a fixed point on the rotor with a speed corresponding to slip frequency. The shape of the distribution remains unaltered. In other words, Fig. 2 can be considered as showing the current distribution in the squirrel-cage at any moment. This distribution remains independent of time.

If the distance between two adjacent rotor bars is $\delta$ electrical deg., and the rotor has an even number of bars per pole, the current in the different bars has the following values:

$$\text{Current in bar } I_1 = I \times \text{sine} \frac{\delta}{2}$$

$$\text{Current in bar } I_2 = I \times \text{sine } \delta + \frac{\delta}{2}$$

$$\text{Current in bar } I_3 = I \times \text{sine } 2\,\delta + \frac{\delta}{2} \quad \text{etc.}$$

These equations are vectorially represented in Fig. 3.

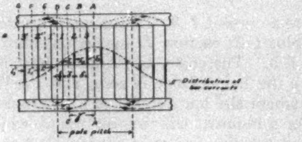

FIG. 2

The vectors 1–2, 2–3, 3–4, 4–5 are alike and are equal to $I$. (*i. e.*, the maximum current which any of the bars can carry), and are displaced against each other by the angle $\delta$. All these vectors form a polygon, the circumference of which approaches the value $2\,Z \times I$, where $Z$ is the number of squirrel-cage bars for one pole. The radius of a circle circumscribing this polygon is, therefore, given by the equation:

$$r = \frac{2\,Z\,\hat{I}}{2\,\pi} = \frac{Z\,\hat{I}}{\pi} \tag{1}$$

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[2] This scheme was originally suggested by Zieglke, see Electric Motors, by H. M. Hobart, p. 314.

*Presented at the A. I. E. E. Regional Meeting, St. Louis, Mo., March 7-9, 1928.*

As shown above the current in bar 1 is $\hat{I}$ sine $\frac{\delta}{2}$.

The current in bar 2 is $I$ sine $\left(\delta + \frac{\delta}{2}\right)$, and the current in bar 3 is $\hat{I}$ sine $\left(2\,\delta + \frac{\delta}{2}\right)$. From Fig. 3 it will be seen that these current values are represented by the lines 2–7, 3–8, 4–9, etc. In other words the projection of the lines 1–2, 2–3, 3–4, 4–5, etc., on the horizontal diameter 0–1 represents the bar currents $I$–1, $I$–2, $I$–3, etc.

From the distribution of the bar currents, as given in Fig. 2, the distribution of currents in the ring can be derived.

For the purpose of symmetry (see Fig. 2), it is permissible to say the current $I$–1 and the current $I$–1′ form one circuit. In the same manner the current $I$–2 in bar 2 completes its circuit with current $I$–2′ in bar 2′, etc. Consequently, the section $A$ of the ring does not carry any currents at all; while the section $B$ carries a current $I$–3; the section $C$ carries the current $I$–3 plus $I$–2; section $D$ carries current $I$–1 plus $I$–2 plus $I$–3. Therefore, the ring current is a maximum where the bar current is zero, and the ring current is zero where the bar current is a maximum. Considering for a moment the ring section $C$, which carries bar current $I$–3 plus $I$–2, we see from Fig. 3 that the current in this section is equivalent to the projection of the chord 2–4 on the base line 0–1. But this can also be considered as the projection of the radius $r$ = 0–2 on the base line 0–10. Thus the current in ring section $C$ can be expressed as

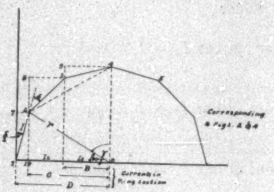

FIG. 3

$$I_c = r\cos(90 - \gamma) = r\sin\gamma \qquad (2)$$

where $\gamma$ is the angle the radius 0–2 forms with the radius 0–4, which is identical to saying the angle $\gamma$ is the distance, measured in electrical deg., from the center of section $C$ to the center of section $A$. By equation (2) it is demonstrated that the current distribution in the rings follows a sine curve, being zero at the point $A$. As seen, previously, the current distribution in the bars follows a sine curve, being zero at the point $D$. Points $D$ and $A$ are 90 deg. displaced from each other. Therefore, if both curves refer to the same starting point, one of the curves is a sine curve and the other is a cosine curve. Substituting in equation (2) the value for $r$ from equation (1), it follows:

$$I_\gamma = \frac{Z\,\hat{I}}{\pi}\sin\gamma \qquad (3)$$

which expresses the ring current at any section $\gamma$ as function of the maximum bar current $\hat{I}$. The loss due to the ring current is at any point proportional to the square of the current. Consequently the loss at any point is obtained by squaring equation (3) and multiplying it with a coefficient $k$, which takes care of the resistance of the ring section under consideration. The loss at any point is, therefore:

$$\frac{Z^2\,\hat{I}^2}{\pi^2}\sin^2 r \times k \qquad (4)$$

The total ring loss is the integral of equation (4) and is given by equation:

$$\text{Loss in one ring per pole} = 2\int_{r=0}^{r=90}\frac{Z^2\,\hat{I}^2}{\pi^2}\sin^2 r\;k\;dr \qquad (5)$$

$k$ = resistance of a ring portion corresponding to a unit angle. Therefore, if $k$ is the resistance of one ring spanning an arc corresponding to one pole pair ($2\,\pi$), we obtain:

$$k = \frac{R}{2\,\pi} \qquad (6)$$

The solution of the integral part of equation (5) is:

$$2\int_{r=0}^{r=90}\sin^2 r = 2\left(\frac{1}{2}\,r - \frac{1}{4}\sin 2\,r\right)^{\frac{\pi}{2}} = \frac{\pi}{2} \qquad (7)$$

Consequently the losses in one ring per pole

$$= \frac{\pi}{2}\,.\,k\,\frac{Z^2\,\hat{I}^2}{\pi^2}$$

Substituting $k = \frac{R}{2\pi}$ from equation (6), it follows:

losses in one ring per pole =

$$\frac{R}{2\,\pi}\cdot\frac{\pi}{2}\cdot\frac{Z^2\,\hat{I}^2}{\pi^2} = \frac{R\,Z^2\,I^2}{4\,\pi^2}$$

and the losses per pole pair and both rings equal:

$$\frac{R\,Z^2\,I^2}{\pi^2}\,.\text{ if }\bar{I} = \hat{I}\,\sqrt{2} \qquad (8)$$

The losses in both rings per pole pair equal:

$$\frac{R\,Z^2\,\hat{I}^2\,2}{\pi^2} \qquad (9)$$

$R$ = resistance of ring spanning two-pole pitches
$Z$ = number of squirrel-cage conductors per pole

$I$ = effective rotor-bar current per pole

The laws established so far are well-known and refer to the current distribution and losses in the bars and rings of a squirrel-cage whose rings are solid, (Fig. 2). The relations are not quite as simple for a squirrel-cage with slotted endings (Fig. 1).

Figs. 4 and 6 show a two-pole squirrel-cage winding with end rings split in the manner described. It has been shown above that the current distribution in the squirrel-cage bars must follow a sine law as long as the current distribution in the stator follows the sine law. The current distribution in the bars is given by the sine curve 2–3–4 (Fig. 4) for the moment when the rotor bar currents are so located that the maximum bar current coincides with the slot $A$ in the ring 1. This distribution is identical to that shown in Fig. 2. It is evident that the ring currents in Fig. 4 must be distributed as shown, which when plotted in a coordinate system as a function of space gives Fig. 5.

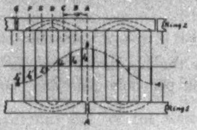

Fig. 4

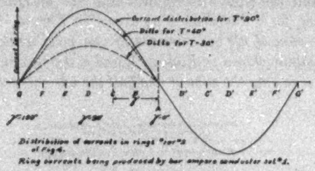

Fig. 5

Conditions change materially if the moment is considered when the sine-shape distribution of the bar currents is so located that the bar carrying no current coincides with the cut $A$ in ring 1, as shown in Fig. 6. With the bar current in this distribution, it is no longer possible that the current $I$–1 and $I$–1′ close symmetrically in rings 1 and 2, as found for Fig. 4. The only symmetrical ring distribution possible with the symmetrical bar distribution is that given in Fig. 6, *i. e.*, section $F$ in ring 2 must carry the bar current $I_1$. The section $E$ carries bar current $I_2$ plus $I_1$; section $D$ carries $I_1$ plus $I_2$ plus $I_3$. Section $C$ carries $I_1$ plus $I_2$ plus $I_3$ plus $I_4$. Section $B$ carries $I_1$ plus $I_2$ plus $I_3$ plus $I_4$ plus $I_5$, and, finally, section $A$ carries the sum of all bar currents of one pole, *i. e.*, $I_1 + I_2 + I_3 + I_4 + I_5 + I_6$.

A more general expression for the currents in the ring section with a bar-current distribution (Fig. 6) is obtainable as follows:

Vectors 1–2, 2–3, 3–4, 4–5, 5–6, etc. (Fig. 7) represent the maximum current in any of the rotor bars. Each vector is drawn against its preceding vector under an angle $\delta$ equal to the displacement of the bars against each other. The vector 1–2 is shown displaced against the vertical 1–7 by an angle $\frac{\delta}{2}$. The current $I_1$ in bar 1 is consequently given by the distance 2–7, and the current in $I_2$ in bar 2 is given by the vector 3–8, etc.

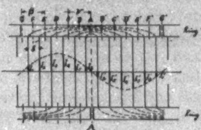

Fig. 6

In other words the bar currents are the projections of the vectors 1–2, 2–3, etc., on the base line 0–1′. So far the diagram is identical to Fig. 3. The current passing through the ring section $F$, as shown above, is equal to the bar current $I_2$. Consequently, it is given by the length 2–7 or 1–10 (Fig. 7), which is the projection of the vector 1–2 on the base line. The current through the ring section $E$ is the sum of bar current $I_1$ and $I_2$. It is consequently given by the length 1–11, which is the projection of the vectors 1–2 and 2–3.

If the currents in the different sections, $A, B, C, D, E,$ and $F$, are plotted as function of their space location, a current distribution in the ring is obtained as shown in Fig. 8. A glance at Figs. 6, 7, and 8 shows the current distribution in the rings must be related in some manner to a sine law. The exact relations are derived mathematically as follows:

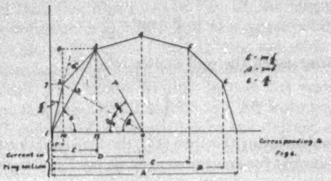

Fig. 7

In Fig. 6 the center of the ring section $E$ is $\beta$ electrical deg. displaced against the point $G$. It follows that in this case $\beta = 2\,\delta$. In the same manner the ring point $D$ is displaced by an angle $\beta = 3\,\delta$, etc. In Fig. 7 the angle $\beta$, of Fig. 6 appears as angle 1–0–3, if the ring section $E$ is under consideration; or an angle 1–0–4 if point $D$ is under consideration, etc. From triangle

1–0–3, it follows that the side 1–3 is given by the equation:

$$(1\text{–}3) = 2\,r \sin \frac{\beta}{2} \tag{10}$$

As the ring current in section $E$ is a projection of the vector 1–3 on the base line,

$$I_\beta = 2\,r \sin \frac{\beta}{2} \,.\, \cos \epsilon \tag{11}$$

But angle $\epsilon$ is related to the angle $\beta$,

$$\epsilon = 90 - \frac{\beta}{2} \tag{12}$$

as can be seen from the triangle 1–0–12. Consequently the cosine of angle $\epsilon$ can be expressed as a function of angle $\beta$. $\cos \epsilon = \cos \left( 90 - \frac{\beta}{2} \right) = \sin \frac{\beta}{2}$ (13)

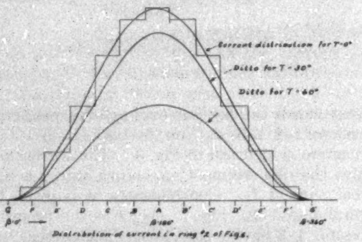

Fig. 8

and this value substituted in equation (11) gives

$$I_\beta = 2\,r \sin^2 \frac{\beta}{2} \tag{14}$$

Making use of the well-known relation

$$2 \sin^2 \frac{\beta}{2} = \left( 1 - \cos \frac{\beta}{2} \right) \tag{15}$$

and substituting this into (14), the final equation for the ring current for an arrangement as per Fig. 6 is given,

$$I_\beta = r\,(1 - \cos \beta) = \frac{Z\,\bar{I}}{\pi}\,(1 - \cos \beta) \tag{16}$$

This equation gives the ring current in a split ring as function of the angle $\beta$ (Fig. 6), and which when plotted in coordinate system gives the curve of Fig. 8. Consequently, the loss at any point of the ring is obtained by squaring equation (16) and multiplying it with the coefficient $k$, which takes care of the resistance of the ring section under consideration, in the manner explained.

The loss at any point of the ring is, therefore,

$$\bar{I}_\beta^2\,k = r^2\,(1 - \cos \beta)^2\,k \tag{17}$$

The total ring loss must be the integral of this equation, *i. e.*,

$$\text{loss in one ring per pole pair} = \int_{\beta=0}^{\beta=360} r^2\,k^2\,(1 - \cos \beta)^2\,d\,\beta$$

$$= k\,r^2 \left[ \int_0^{360} d\,\beta + \int_0^{360} \cos^2 \beta\,d\,\beta - \int_0^{360} 2 \cos \beta\,d\,\beta \right]$$

$$= k\,r^2\,[2\,\pi + \pi + 0 - 0] = 3\,\pi\,r^2\,k \tag{18}$$

Consequently the loss in one ring per pole pair equals $3\,r^2\,k$, or loss per pole pair and both rings equal

$$6\,\pi\,r^2\,k \tag{19}$$

Substituting $k = R/2\,\pi$ from equation (1) and $r = \dfrac{Z\,\bar{I}}{\pi}$ from equation (6), we find, losses for both rings per pole

$$\text{pair} \quad = \frac{3\,R\,Z^2\,\bar{I}^2}{\pi^2} = \frac{3\,R.Z^2\,\bar{I}^2\,.\,2}{\pi^2} \tag{20}$$

This equation compared with (8) shows that the ring loss for a current distribution (Fig. 6) is three times as large as the ring loss for a current distribution, (see Figs. 4 & 5).

From the above it follows that *the maximum ring current, for a distribution as shown in Figs. 6, 7, and 8, is the sum of all bar currents of one pole; while for the distribution shown in Figs. 3, 4, and 5, the maximum ring current is only the sum of one-half the bar currents of one pole.* The losses in one ring must vary from time to time: At one moment the distribution of the ring current in ring No. 2 is that given in Fig. 4, and 90 electrical deg. later the current distribution in the ring No. 2 and bars is as shown in Fig. 5. In order to determine the actual loss in the rings, it is to be remembered that a rotating sine-shaped field can always be considered as being made up of two alternating sine-shaped stationary fields, which are located at right angles to each other and the alternations of which have a 90 deg. time displacement. Consequently, sine-shaped distributed

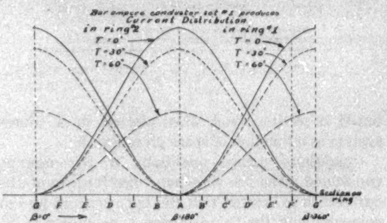

Fig. 9

rotating ampere conductors (bar currents are under discussion) can be considered as being made up of two sets of ampere conductors:

Set No. 1, whose axis is located as per Fig. 4, *i. e.*, the maximum of the ampere conductors coincides with the slot *A* in the ring.

Set No. 2, whose axis is located as per Fig. 6, *i. e.*, it is 90 electrical deg. displaced from the slot *A*.

The ampere conductors of each one of these two sets must vary in time according to the sine wave, or cosine law, and the amperes in a given section of a ring must also vary with time in accordance with the sine or cosine law. For instance, for Fig. 4 the ring current distribution in space is given by Fig. 5. For the time $T = 0$, it has been assumed that the current is zero; for the time $T = 90$ deg., the current distribution has reached its maximum; and for the time $T = 30$ and $T = 60$, the distributions lie between the two mentioned extremes.

In a similar manner, current distributions in a split ring vary from time to time. For the time $T = 0$ the distribution is represented by the heavy curve in Fig. 8.

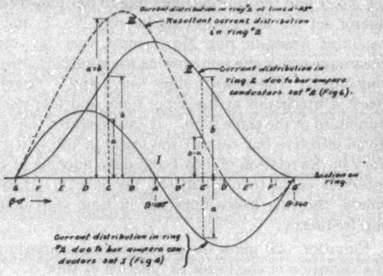
Current distribution in ring #2 at time α=45°
III
Resultant current distribution in ring #2
II
Current distribution in ring 2 due to bar ampere conductors set #2 (Fig 6).
a+b
b
a
I
b
b−a
a
G
F
E
D
C
B
A
B'
C'
D'
E'
F'
G'
Section on ring.
β=0 →
β=180
β=360
Current distribution in ring #2 due to bar ampere conductors set 1 (Fig 4)

Fig. 10

This figure also shows the distribution for the time $T = 30$ deg. and $T = 60$ deg. For the time $T = 90$ deg., the current distribution is zero and is equivalent to the base-line of Fig. 8 diagram.

In discussing the current distribution in a split ring, reference was made to ring No. 2 in Fig. 6. It remains to be seen if the same current distribution also exists in ring No. 1 of Fig. 6. For reasons of symmetry, the current distributions in rings Nos. 1 and 2 must have the same general shape. However, the curve representing the current distribution in ring No. 1 must be displaced 180 electrical deg. against the curve representing the current distribution in ring No. 2, because it is seen that the current in ring No. 1 is zero at point *A* and the current in ring No. 2 is a maximum at point *A*. The distributions of rings Nos. 1 and 2 for a given time instant are given in Fig. 9.

For the unsplit ring, (Figs. 3, 4, and 5,) the current distributions in corresponding sections in rings Nos. 1 and 2 are the same and are not displaced against each other.

In reality the ring distributions, as shown in Figs. 4 and 6, occur simultaneously. Consequently the resultant current distributions in each ring must be the sum of the currents in a given ring section, as found from Figs. 4 and 5, and the current in the same ring section as found from Figs. 6 and 9.

In this manner the distribution of the currents in ring No. 2 is obtained as shown in Fig. 10, where curve *I* represents the distribution in ring No. 2, due to the ring currents produced by the bar ampere conductor set No. 1, which, in turn, corresponds to the arrangement shown in Fig. 4. The curve II in Fig. 10 represents the current distribution in ring No. 2 due to ring currents produced by the bar ampere conductor set No. 2, which, in turn, corresponds to the arrangement shown in Fig. 6. Curve III, finally, represents the sum of the ordinates of curves I and II and represents for a certain time instant the resultant current distribution in ring No. 2. For a different time instant, the resultant ring distribution has a different shape, as follows:

As the time when ampere conductor set No. 1 is zero, ampere conductor set No. 2 is a maximum. The resultant distribution in ring No. 2 at this moment must be, therefore, as shown in Fig. 8, curve marked $T = 0$. Similarly, for the instant when ampere conductor set No. 1 is a maximum, ampere conductor set No. 2 is zero, the resultant distribution in ring No. 2 is, for this moment, as the curve marked $T = 90$ in Fig. 5. In Fig. 10, a time moment $\alpha = 45$ deg. has been selected, so as to have neither curve I nor II equal to zero. For this time moment, the maximum value of curves I and II happens to be equal to 70.7 per cent of the absolute maximum which they reach for the time $\alpha = 0$, and $\alpha = 90$ deg.

It must be clearly understood that for any other time instant than that illustrated in Fig. 10, the magnitude of the ordinates of curves I and II changes, while the relative shape of curves I and II does not alter. On the other hand, the shape and the magnitude of curve III alters with time. At any instant the resultant current flow in any ring section say, for instance, section *C*, consists of a current due to the current corresponding to curve I, *i. e.*, equal to $a$, and a current due to curve II, *i. e.*, equal to $b$. The total instantaneous current in ring section *C* is, therefore, $a + b$. The instantaneous loss in the ring section *C* is proportional to the square of the resultant current and, hence, is proportional to $(a + b)^2$.

If a corresponding ring section *C'* is selected—which is so located that its distance from the symmetry line *A* is the same as the distance of the point *C* from the symmetry line *A*—the instantaneous current in section *C'* is $b - a$, and the loss in this section is proportional to $(b - a)^2$. Consequently, it can be said: Loss in section *C* proportional to $(a + b)^2$

$$= (a^2 + b^2) + 2\,a\,b.$$

Loss in section $C'$ proportional to $(a - b)^2$

$$= (a^2 + b^2 - 2\,a\,b).$$

The combined loss in sections $C$ and $C'$ is the sum of the losses in $C$ and $C'$ and is given by:

$$\text{Loss in section } C \text{ and } C' = 2\,(a^2 + b^2). \qquad (21)$$

This equation demonstrates that *the sum of the instantaneous losses in any two symmetrically located ring sections equals the sum of the losses produced independently in each section by the ring currents a and b.*

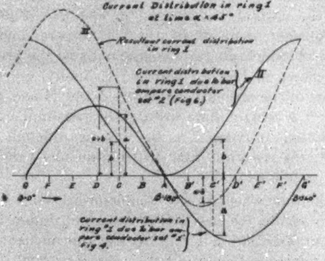
Current Distribution in ring 1 at time α = 45°
III
Resultant current distribution in ring 1
Current distribution in ring 1 due to bar ampere conductor set #2 (Fig 6.)
II
a+b
b
a
G
F
E
D
C
B
A
B'
C'
D'
E'
F'
G'
β=0°
β=180°
β=360°
a-b
Current distribution in ring #1 due to bar ampere conductor set #1 Fig 4.

FIG. 11

Consequently, the total losses in ring No. 2, at any moment, is equal to the sum of the instantaneous ring losses due to currents I and II. As the magnitude of the currents represented by curve I, Fig. 10, changes in time according to a sine law, it follows that the losses due to these ring currents change in time as,

$$L_1 = \bar{L}_1 \sin^2 \alpha \qquad (22)$$

where $\bar{L}_1$ is the maximum loss which occurs in the ring, that is, which occurs at the time $\alpha = 90$ deg. Similarly, the currents corresponding to the distribution curve II, Fig. 10, change in time in accordance with the cosine law. The losses due to the currents corresponding to curve II are given,

$$L_2 = \bar{L}_2 \cos^2 \alpha \qquad (23)$$

where $\bar{L}_2$ is the maximum loss which occurs in the ring due to the bar ampere conductor set No. 2. Previously it was shown by equation (**20**) that a fixed relation exists between $\bar{L}_1$ and $\bar{L}_2$, and that $\bar{L}_2$ is three times as large as $\bar{L}_1$. In other words,

$$\bar{L}_2 = 3\,\bar{L}_1 \qquad (24)$$

The total loss in ring No. 2 at any time $\alpha$ must be the sum of the losses given by equations (**22**) and (**23**). Substituting for $L_2$ the values from equation (**24**), we obtain,

$$\begin{aligned} L_1 + L_2 &= L_1, \sin^2 \alpha + 3\,L_1 \cos^2 \alpha \\ &= L_1\,(\sin^2 \alpha + \cos^2 \alpha + 2 \cos^2 \alpha)\; L_1 + L_2 \\ &= L = 1 + 2 \cos^2 \alpha \qquad (25) \end{aligned}$$

The results of equation (**25**) are graphically represented in Fig. 12. It will be seen that the resultant loss in ring No. 2 fluctuates between the extremes of $3 \times \bar{L}_1$ and $\bar{L}_1$. The time intervals between two successive maxima correspond to one-half slip periodicity.

So far the losses were derived for the current distributions existing in ring No. 2. It was shown that the current distribution in ring No. 1 due to bar ampere conductor set No. 2 is the same as in ring No. 2, but is 180 deg. displaced in space against the distribution in ring No. 2, as shown in Fig. 9.

The ring current distribution in rings Nos. 1 and 2, due to the bar ampere conductor set No. 1, are, however, identical in every respect.

Consequently the resultant current distribution in ring No. 1 is as shown in Fig. 11. In Fig. 10 the curve I passes through zero where curve II is a maximum, while in Fig. 11 curves I and II pass through zero at the same point. Selecting again two symmetrically located sections $C$ and $C'$ on the ring No. 1, the instantaneous currents in these ring sections are respectively $a$ and $b$. The losses in these sections are $(a + b)^2$, and $(a - b)^2$. Consequently, the law – that the resultant instantaneous losses are the sum of the instantaneous losses of the ring currents due to bar ampere conductor set No. 1 and the ring currents due to bar ampere conductor set No. 2,—also exists for ring No. 1; and the resultant losses in ring No. 1 must vary in time in accordance with the same law as the resultant losses in ring No. 2. The losses in rings Nos. 1 and 2, therefore, reach a maximum at the same time, and also reach a minimum at the same time. It can be stated that for a given effective bar current the losses in the split rings vary in the relation of 3 to 1 and have maxima at time intervals equal to one-half slip periodicity. In other words, the ring losses fluctuate in time with double-slip frequency.

Equation (**25**) gives the mathematical expression for the variation of the losses as function of time $\alpha$. This equation contains the factor cosine² $\alpha$. It is a well-known fact that the average ordinates of a cosine² $\alpha$ curve are one-half of the maximum ordinates. Consequently the average loss in the rings is given by the equation,

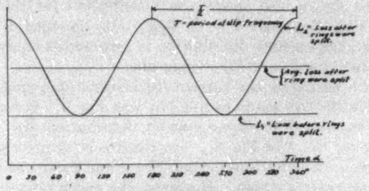

FIG. 12

$$(L_1 + L_2)_{\text{avg.}} = 2\,\bar{L}_1 \qquad (26)$$

This equation shows the important fact that the *average* ring loss in a squirrel-cage with split rings is two times as large as the losses in an unsplit ring, as long as the effective currents in the bars are kept constant.

As these laws are derived for the losses occurring with a given effective current in the bars, it is evident that the same laws also apply to the resistance which the split rings of the squirrel-cage offer. It is, therefore, correct to say *the ring resistance of a squirrel-cage with split rings varies in the ratio of 3 to 1 with a frequency of two times slip frequency. The average ring resistance is equal to two times the resistance of an unsplit ring.*

FIG. 13

Consequently with *absolutely constant rotor speed*, the effective value of the bar currents fluctuates with double-slip frequency, which in turn means that the rotor torque fluctuates with double-slip frequency. Such a condition exists when the inertia of the rotor and the driven machinery is very large and tends to keep the rotor speed constant in spite of the fluctuating torque which acts on the rotor.

On the other hand, when the rotor and the driven machine have infinitely small inertia and the mechanical load torque is held constant, the slip of the machine must vary periodically and the rotor bar currents remain constant in order to produce constant torque.

In the latter case, an oscillogram of the primary line current must show a constant magnitude of alternating current. In the former case, where the inertia is infinitely large, the oscillogram of the line current must show a variation of the a-c. value and the magnitude of this alternating current fluctuates periodically in time.

FIG. 14

In practise the conditions lie between the two extremes just discussed, that is, the speed and the current changes. As a rule these changes will not be found very objectionable.

The higher the average slip, the faster are the torque impulses, and the greater is the tendency for the machine to run at constant speed.

An oscillogram of the full load line current taken on a 7½-hp., four-pole, 60-cycle, 2-phase, 220-volt, squirrel-cage motor with split rings is shown in Fig. 14. The fluctuations in the magnitude of the line current is clearly shown in this oscillogram. Fig. 13 shows the line current on the same machine, but provided with a squirrel-cage without split rings. No fluctuations whatsoever are noticeable in this case in the magnitude of the line current.

At the same time that the oscillogram of Fig. 14 was taken, the slip on the motor was also observed and found to be 4.4 per cent. It was measured by the stroboscopic method, and the white cross on the pulley used clearly showed a periodic swing, indicating that the speed of the motor fluctuated. The relations on the motor under test were such that the inertia was not sufficiently great to damp out completely the speed fluctuations. The oscillogram shows that the time between two current maxima, *A* and *C*, equals approximately 11 times the time between two adjacent 60-cycle current maxima, *A* and *B*. Consequently, the periodicity of the "breathing" of the line current is 1/11 = 9.1 per cent or 9.1/4.4 = 2.06 times the measured slip frequency. The theoretical value of this ratio according to the above theory is 2. The agreement between test and theory is satisfactory.

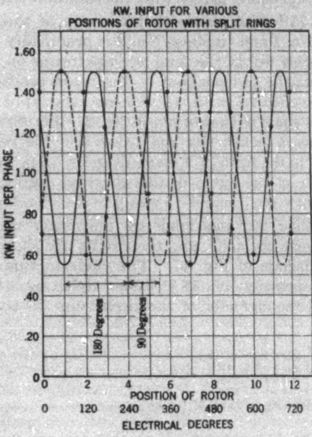

FIG. 15—7½ HP.—4 POLE—220 VOLT—60 ~2 Φ
1725 REV. PER. MIN.

Fig. 15 gives the kw. input to phases No. 1 and 2 when the rotor is locked and the rings are split. The results are plotted as function of rotor position. This plot shows that the kw. input of a given phase depends on the position of the rotor, and the maxima are displaced one-pole pitch or 180 electrical deg. This is in full agreement with the theory. The plot also shows that the maxima of phase No. 1 is displaced 90 electrical deg. against the adjacent maxima of phase No. 2. This also is in full agreement with the above theory, which shows that the minimum, or maximum, resistance of the squirrel-cage corresponds to two a-c. fields 90 electrical deg. displaced against each other.

From the maximum readings from phase No. 1, (corresponding to position 1-4-7), and the minimum reading of phase No. 2 (corresponding to the same rotor position), it is calculated that the equivalent rotor resistance expressed in primary turns is 1.62 for phase No. 1 and 0.565 for phase No. 2. Consequently, the ratio of resistance variation is 1.62/0.565 = 2.82. The theory showed that the rotor resistance, when only the rings are considered, must vary in the ratio of 1 to 3; but if the bars also are considered, the resistance naturally must vary in a ratio less than 1 to 3. The theory, therefore, agrees with the results found by test.

Fig. 15 further shows that the sum of the input to phase No. 1 and to phase No. 2 is practically constant or, in other words, the total average torque on the rotor is practically independent of the rotor position. For rotor position 1.6, 3.15, 4.7, 6.3, etc., the input to phase No. 1 is equal to that of phase No. 2. For one of these positions, a locked test was taken and the results are plotted in the form of a circle diagram (Fig. 16). The diameter of the circle of this diagram corresponds to 38 kv-a.

A similar test was made on the motor using rings which were not split, and the results are shown in the circle diagram of Fig. 17. The circle in this diagram has a diameter of 48.3 kv-a. Splitting the rings reduced the diameter of the circle from 38 to 48.3, or to a value of 79 per cent of the original value before the rings were split. This is equivalent to stating the leakage of the motor with split rings is 1/.79 = 1.27 times that of the same motor before the rings were split. Similar tests made on a number of other machines of different ratings and speeds also have shown an increase in leakage. It is, therefore, justifiable to say the splitting of the rings not only increases the average ohmic resistance of the rings in the ratio of 1 to 2, but also increases the leakage of the machine. Consequently, the actual gain in starting torque due to splitting the rings must be less than the increase in average rotor resistance. In the machine whose test data are recorded in this paper, the increase in leakage counteracted completely the increase in rotor resistance, and the net result was that the rotor with split rings had a starting torque corresponding to 10.68 kw., while the same motor with rings which were not split had a starting torque corresponding to 11.4 kw. Splitting the rings in this particular case increased the leakage so much as to more than counteract the increased rotor resistance. The starting torque of the motor provided with split rings was less than that of the motor with rings which were not split.

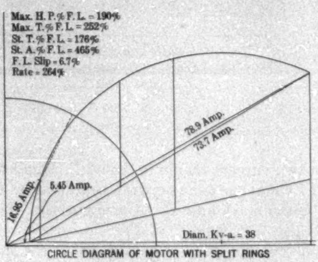

FIG. 16—7½ HP.—4 POLE—220 VOLT—60 ~2 Φ
1725 REV. PER. MIN.

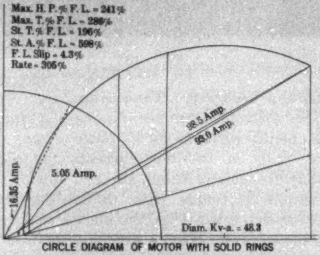

FIG. 17—7½ HP.—4 POLE—220 VOLT—60 ~2 Φ
1725 REV. PER. MIN.

The only beneficial effect obtained by splitting the rings in this case was a better torque per ampere. Before the rings were split, the torque per ampere was 11.4/9.85 = 1.16; and after the rings were split, the torque per ampere was 10.68/7.89 = 1.35. It is self-evident that the increase in leakage and rotor resistance must be followed by a decrease in maximum hp. output. For the tested machine, the circle diagrams show that the split rings decreased the maximum hp. to 78 per cent of the value which existed before the rings were cut. This figure, derived from the diagram, checked very closely with an actual brake test taken on the machine.

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## Discussion

**D. D. Clarke:** I was very much interested in Mr. Weichsel's paper, because of the rather novel presentation of what, in the field, we think of as a repair trick to make a motor start a given load. I felt, in reading the paper, that Mr. Weichsel did not intend this as a normal production motor. The operating company has a contact with this motor that the manufacturer might not think important, and that is the varying current or breathing effect, as Mr. Weichsel puts it.

This breathing occurs three to five times per second and incandescent lamps are particularly sensitive to such breathing of the voltage. Even though it may vary only a half or one per cent, this, in a critical location, could make a very unsatisfactory condition on a public utility's lines. The difficult thing would be that replacement would be required to correct it. In a way, it is parallel to a trouble job on a wound-rotor motor where the secondary winding is open. This same sort of breathing action takes place because of the variation in the losses in the secondary of the induction motor.

Tampering by a repair man with the design features of a motor, does not improve conditions. In this case, the horsepower rating of the motor was reduced and the actual starting power was reduced.

**K. L. Hansen:** It has been clearly brought out in the paper that the splitting of the end rings in the manner suggested has certain detrimental effects on the operation of the motor when running at its normal load and speed. For that reason it has apparently been very little used. Nevertheless it may at times be the means of overcoming some specific difficulty, and it therefore becomes very desirable for a designing engineer to know just what can be expected in the way of remedying the trouble, as well as the detrimental effects that are likely to result from the application of this method. I feel, therefore, that the author deserves credit for analyzing this problem.

With regard to the method used in the paper of arriving at the resistance of the end rings, perhaps, some might prefer to use shorter and more direct methods. For example, it can be seen at once from Fig. 4 in the paper that the maximum current in the ring at Section D is the sum of the average current in the rotor bars over one-half the pole pitch. Using Mr. Weichsel's notation of $\bar{I}$ to denote the maximum current in the rotor bars, the average current then is $\frac{2\,\bar{I}}{\pi}$. If $Z$ be the number of bars over one pole pitch, the maximum current in the end ring will then be $\frac{Z\,\bar{I}}{\pi}$. From this it follows that the effective current in the end ring is $\frac{Z\,\bar{I}}{\sqrt{2}\,\pi}$. Squaring this and multiplying by $\frac{R}{2}$, this being the resistance spanning one pole pitch, we have $\frac{R\,Z^2\,\bar{I}^2}{4\,\pi^2}$ as the losses per pole in one ring, which is identical with the result arrived at in the paper.

In the same way inspection of Fig. 6 of the paper will show that the maximum current in the ring in this case is equal to the sum of the average current in the rotor bars taken over one whole pole pitch, or twice as high as with the distribution shown in Fig. 4. It will also be seen that at any given instant the current in the end ring is always in the same direction. The current distribution in the end ring in this case varies sinusoidally from zero to a maximum value equal to twice that of the previous case, and hence can be expressed by

$$\frac{Z\,\bar{I}}{\pi} - \frac{Z\,\bar{I}}{\pi}\cos\beta$$

where $\beta$ is the angle in electrical degrees measured along the end ring with the section $G$ taken as reference. This current is seen to consist of two components, the first one being constant and having an effective value, $\frac{Z\,\bar{I}}{\pi}$, the second one varying sinusoidally and having an effective value, $\frac{Z\,\bar{I}}{\sqrt{2}\,\pi}$. The loss due to this current distribution is the sum of the losses of these two components and the loss per pole in one ring is, therefore,

$$\left(\frac{Z^2\,\bar{I}^2}{\pi^2} + \frac{Z^2\,\bar{I}^2}{2\,\pi^2}\right)\frac{R}{2} = \frac{3\,R\,Z^2\,\bar{I}^2}{4\,\pi^2}$$

which is seen to be three times as high as the losses corresponding to the current distribution shown in Fig. 4.

That the losses in the end ring due to "ampere-conductor set No. 1" and those due to "ampere-conductor set No. 2" can be considered separately may also be briefly shown by a similar line of reasoning. However, to some these shorter methods may not seem sufficiently conclusive, in which case they have recourse to the more detailed methods used by Mr. Weichsel in his paper.

It has then been shown that with the end rings split as suggested the rotor may be considered as being made up of two distinct circuits displaced 90 electrical deg. from one another and one circuit having an end-ring resistance three times as high as the other. In other words, the case is exactly equivalent to a slip-ring motor with two-phase rotor and unequal resistances in the two phases. If $I_1$ be the current flowing in the circuit of low resistance and $I_2$ the current flowing in the high-resistance circuit, the magnetizing force of the combined rotor currents can be shown to consist of two components, a forwardly rotating component equal to $\frac{\bar{I}_1 + \bar{I}_2}{2}$ and a backwardly rotating component equal to $\frac{\bar{I}_1 - \bar{I}_2}{2}$.

This backwardly rotating component of rotor m. m. f. rotates on the rotor at a speed corresponding to slip frequency, but as the rotor is slipping behind the main rotating field at the same rate, it follows that the relative motion between the main field and the backwardly rotating magnetizing force must be equal to twice the slip. As the poles of this magnetizing force pass the poles of the main rotating field of the same and alternate polarities, a pulsating torque is developed, the rate of pulsations being equal to twice the slip frequency. The amplitude of this torque pulsation is proportional to the product of the main field and the backwardly rotating component of the rotor m. m. f. It is responsible for the pulsations in the speed and line current discussed by Mr. Weichsel.

Besides being responsible for the speed and torque pulsations, this backwardly rotating component of the secondary magnetic field, causes some other interesting phenomena that have not been brought out in the paper. The average value of the torque pulsations is zero and the speed-torque curve is not affected by them. This curve may, nevertheless, be greatly modified by the backwardly rotating component of the secondary field. This can, perhaps, be best observed by taking an extreme case of unbalancing of the rotor circuits, that is by opening one of these circuits entirely and running the machine with single-phase rotor. In that case the backwardly rotating component of secondary m. m. f. is equal to the forwardly rotating component.

The backwardly rotating component of rotor m. m. f. produces a magnetic field of greater or less intensity, which generates a current in the primary of frequency $(2\,s - 1)$ times the line frequency, where $s$ is the slip. The voltage generated in the primary winding being proportional to the frequency, becomes equal to zero at half speed.

The intensity of the backwardly rotating field depends on the strength of the m. m. f. producing it and on the reaction of the current produced by it in the primary circuits. As there is no current generated in the primary by this field at half speed, it reaches its maximum intensity at this point and would reach very high values if it were not limited by saturation. The fact that saturation enters in and greatly modifies the mutual inductance between primary and secondary windings near the half-speed point makes the torque developed by the backwardly rotating field somewhat difficult to calculate in this region.

However, as soon as the speed departs, even slightly, from the half-speed point, currents will flow in the primary which by their damping action reduce the field strength below the saturation point. Under these conditions it can readily be seen that if $I_1$ be the secondary current in terms of the primary, the current generated by the backwardly rotating field is

$$I_0{}^1 = I_1 \left[ \frac{(2s-1)\,X_m}{r_0 + j(2s-1)\,(X_m + x_0)} \right]$$

where $X_m$ is the mutual reactance at full frequency, $r_o$ the primary resistance, and $x_o$ the primary reactance. The primary resistance loss resulting from this current divided by $(2s - 1)$ gives the torque (synchronous watts) developed by the backwardly rotating field at any speed. Below half speed this torque component is in the same direction as the motor torque, at half speed it becomes zero, and above half speed there is a generator action and it is in opposition to the main motor torque. For example, in Fig. 1 herewith is shown the speed-torque curve of a motor operating on single-phase secondary and having approximately the same constants as the motor used for illustration in Mr. Weichsel's paper. Curve *a* is the torque curve with balanced polyphase secondary. Curve *b* is the torque developed by the forwardly rotating field when operating with single-phase secondary, and curve *c* is the torque developed by the backwardly rotating component. The resultant of the last two, curve *d*, is the actual speed-torque under this condition.

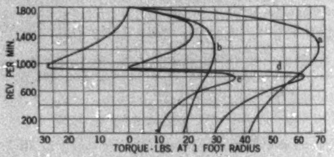


FIG. 1

It will be noticed that the resultant torque is zero at half speed, and if started from standstill the motor will not accelerate past this point unless external means are employed. Whether or not a motor will in general stick at half speed when operating on single-phase secondary depends on the secondary resistance. Is this is relatively high the motor may come up to full speed.

It should also be observed that the torque pulsations are most prevalent when the damping effects of the currents induced in the primary reduce the intensity of the backwardly rotating field to a low value, as for example near synchronism. When this damping effect is small, so that the backwardly rotating field approaches the forwardly rotating field in intensity, as for example near the half-speed point, the torque pulsations disappear.

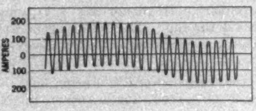


FIG. 2

A number of interesting points about a motor operating under this condition have been brought out by Gazda in a paper *Performance of Polyphase Induction Motors under Unbalanced Secondary Conditions*, (A. I. E. E. TRANS., Vol. XXXVI, 1917, p. 339). An oscillogram in that paper of the primary current taken with a rotor running at half speed plainly shows the low-frequency component generated by the backwardly rotating field of the rotor. It does not show any evidence of torque pulsations causing variations in the amplitude of the primary current similar to those indicated in the oscillogram shown by Mr. Weichsel which was taken with the motor running near synchronism. Fig. 2 herewith shows part of the oscillogram reproduced from Mr. Gazda's paper.

Fig. 3 herewith shows three speed-torque curves, also reproduced from the same paper, taken on a 50-hp., 60-cycle, six-pole motor. Curve No. 1 was taken with all three phases of the rotor short-circuited, curve No. 2 with balanced resistances in the three rotor circuits, and curve No. 3 was taken with single-phase secondary. It is interesting to note that the falling off of speed with increasing load is smaller when the machine is operating at half speed on single-phase secondary than when operating near synchronism with all the rotor phases short-circuited.

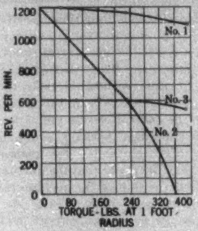


FIG. 3

Returning now to the case of a rotor with split end rings, or unbalanced rotor resistances, it is evident that the phenomena of single-phase rotor operation enter in, only, of course, to a much less marked degree. The current generated in the primary can in that case be approximately expressed by the following formula

$$I_o{}^1 = \frac{I_1 - I_2}{2} \left[ \frac{(2s-1)\,X_m}{r_o + j(2s-1)\,(X_m + x_o)} \right]$$

Fig. 4 herewith shows how the speed-torque curve would be modified on a motor similar to that discussed by Mr. Weichsel. Below half speed the torque will in general be increased so that the accelerating torque in that range is greater. At half speed there is a dent in the speed-torque curve and above half speed the torque will be considerably less than with normal operation. The detrimental effects are, therefore, as pointed out in the paper, reduced speed at full load, reduction in maximum power output, and reduced maximum torque in the upper stable range of the speed-torque curve.

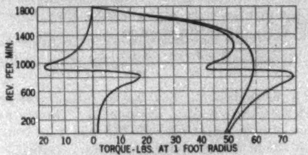


FIG. 4

The starting torque, it appears, may be increased or slightly reduced. Even when the starting torque is reduced, which would seem to be rather the exceptional case, the accelerating torque in the range from standstill to half speed is in general increased. This may in some instances be helpful in overcoming trouble due to sub-synchronous speeds, and the scheme has occasionally been used for this purpose.

The following figures given me by Mr. Oesterlein will show the locked readings on a motor on which the end rings had been split to overcome trouble due to sub-synchronous speed.

Before splitting the end rings—438 volts, 5.4 amp., 3.32 kw., 81 per cent power factor, 10.7 ft-lb. torque.

After splitting the end rings—440 volts, 4.25 amp., 2.53 kw., 77.5 per cent power factor, 12.25 ft-lb. torque.

In addition to showing a higher starting torque after splitting the end rings, the motor accelerated its load much more rapidly than when solid end rings were used.

Mr. Weichsel mentions only one beneficial effect from splitting the end rings, namely that of better starting torque per ampere. I believe we would be justified in adding one more, that of better accelerating torque.

**J. L. Hamilton:** As Mr. Weichsel has pointed out, the results of tests and analysis on squirrel-cage motors with split-end-ring rotors give, as one would expect, the effect of a high-resistance rotor.

His curves and data show lower maximum torque, lower maximum horsepower, and higher static torque per ampere for the rotor with split end rings.

The data show the magnetizing current with split end rings as being about 8 per cent higher than for solid end rings. One would expect the magnetizing current to be substantially the same.

Mr. Hansen in his discussion of this paper has very well pointed out the tendency for sub-synchronous load torque points when rotors with split end rings are used.

On account of the heavy static and pull-in torque requirements for induction motors, along with a minimum of starting current, it is necessary for the designer to avoid low-torque points very carefully. A designer, therefore, would be very careful in employing split-end-ring rotors in general-purpose motors. Central-station engineers are very desirous of keeping static and starting currents of motors to a minimum and would not look with favor, of course, on a motor with low-torque points, since this would mean large starting current per unit of starting torque.

**P. L. Alger:** (by letter) I think the general conclusions we may draw from this paper are, first, that any dissymmetry of the rotor design introduces so much extra reactance as to be distinctly harmful, and, second, that any dissymmetry in the rotor causes double-slip-frequency pulsations of torque and of line current. Practically all single-phase motors have a distinct double slip frequency "beat" in the noise they produce. It is probable that this beating is due to rotor dissymmetries.

It has often occurred to me that any dissymmetries in the rotor, or the use of high-impedance end rings, may cause cross currents to flow between squirrel-cage bars through the rotor punchings, and that these currents may account for various secondary phenomena, such as extra losses. Early induction motors were nearly all provided with insulated squirrel-cage bars, and this practise is still followed by many European manufacturers, the idea being presumably to avoid the possible detrimental effects of such cross currents between bars.

I should like to inquire whether Mr. Weichsel has had any experience indicating that these currents are of appreciable magnitude. I should think that they would be sufficiently large with a split-end-ring construction to affect materially the motor performance.

**W. L. Upson:** I think that we might find, one of these days, when we go over this paper from another point of view, that we might want to extend the investigation and exaggerate the very defects that are outlined here. For example, some use might come of exaggerating the pulsations in connection with induction generators, or perhaps if we made some other splits in the rings, differing from the 90-deg. splits that the author has mentioned. I therefore want to put in this thought, that we have here an extension of our knowledge that later on may be of direct value to us.

**B. T. McCormick:** Mr. Hansen has suggested a "short-cut" method of obtaining the effective resistance of a squirrel-cage rotor, which is similar to the method which I have always used. However, I have never had occasion to determine the resistance of a split-ring squirrel-cage rotor, either by the method suggested by Mr. Hansen or by any other method.

Mr. Hanson calls attention to the tendency of this motor to partake in some degree of the peculiarities of a motor with a single-phase rotor, and its probable tendency to hang at half speed. Mr. Weichsel did not make any experiments on this motor to determine its torque at intermediate speeds, and I am inclined to agree with Mr. Hansen that this motor might have some tendency to hang at half speed, but whether slight or decidedly marked, I cannot say.

Mr. Hansen also remarked that the leakage reactance of this motor is the same as that of a normal motor and that the greater leakage reactance mentioned in Mr. Weichsel's paper is really not such, but merely an effect due to the presence of a backward rotating component. This is merely another way of describing the same action. It is usually easier to combine all the various actions and express their effect as one net result, and the best method of stating the present action is to say that the machine, when tested, gives a circle of smaller diameter than the standard motor, which means that in effect it has a greater leakage reactance.

Mr. Alger asked regarding the effect due to stray currents brought about by not having insulated rotor bars. No investigation along this line has been conducted. I can easily imagine that there would be a tendency for the currents to stray from their proper paths in the squirrel-cage winding in an endeavor to find short cuts through the iron, to follow as closely as possible the natural symmetrical current distribution of the standard squirrel-cage construction. Some effect of this kind probably takes place, and if one were to build two split-ring squirrel-cage rotors, one with uninsulated bars and another with insulated bars, it would not be surprising to find that these rotors when tested show somewhat different performances.

There is one other point that I am rather surprised has not been mentioned by someone, and that is the difficult problem of bracing the split rings to withstand the action of centrifugal force, especially at high speeds. This, I think, is one of the most important criticisms against this type of rotor.

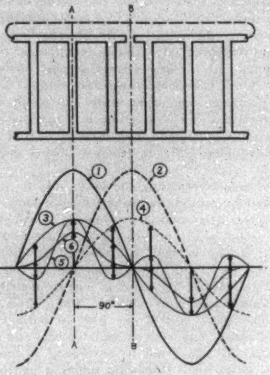
**R. E. Hellmund:** (communicated after adjournment) In the beginning of the paper by Mr. Weichsel, the assumption is made that the currents in the squirrel-cage bars are distributed according to a sine curve (see Figs. 2, 4, and 6). This assumption is not quite correct, as is shown in the accompanying Figs. 5 and 6.

In order to simplify the matter as much as possible, a two-pole rotor with three squirrel-cage bars per pole has been assumed. Under the assumption of a sinusoidal primary field, the voltages in the squirrel-cage bars can be assumed to follow a sinusoidal curve. The currents flowing in the bars have then been calculated by a simple application of Kirchhoff's laws, first assuming that all the resistance is in the bars; secondly, that all the resistance is in the rings; and thirdly, that the resistance is equally distributed between the bars and the rings. The results of this calculation are shown in Fig. 6. It will be seen that while the currents correspond to a sine curve in the axis $(B\ B)$, such is not the case in the axis $(A\ A)$ except in the case where all the resistance is in the bars.

These data are not given primarily to indicate that the results derived in the paper depart materially from actual facts. This I have not checked in detail, and I believe that unless the resistance of the end rings is a very material part of the total, most of the conclusions given in the paper are essentially in line with facts. The principal reason for showing the attached Fig. 6 is that it permits the bringing out of a number of points not touched upon in the paper.

The figure shows that with currents as actually flowing under different conditions, the rotor m. m. f. is different in the two axes at right angles to each other and that such difference is influenced by the percentage of the total resistance put into the end rings. This feature of the secondary m. m. f. is the same condition as would be obtained, for instance, in a two-phase wound secondary having different resistances in the two phases. In other words, the splitting of the end rings brings about conditions which are equivalent to an unbalanced wound secondary. This being the case, a number of facts can be derived which have been fully appreciated for some time in connection with unbalanced wound secondaries.

An extreme example of unbalanced wound secondary is a single-phase secondary. This case has been described in a very simple manner by B. G. Lamme in an article in the *Electric Journal* of September, 1915. Fig. 7 given here is reproduced from this article.



FIGS. 5 AND 6.

1. Bar voltages at one instant of time
2. Bar voltages 90 deg. later
3 and 4. Bar currents, all resistance in bars
5 and 4. Bar currents, all resistance in end-rings
6 and 4. Bar currents, resistance equally divided between bars and end-rings

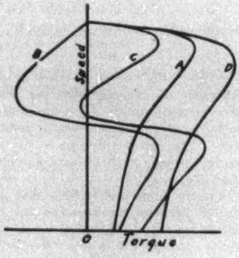


FIG. 7

It will be recalled that the resultant speed-torque curve $C$ of the motor with single-phase secondary is the sum of two component curves $A$ and $B$; curve $D$ represents the same motor with polyphase secondary. If the secondary is not single-phase but merely unbalanced polyphase, the same conditions apply qualitatively, but to a lesser degree quantitatively. In other words, the curve $C$ will not actually indicate negative values above one-half synchronous speed, but there will merely be low torque points, or what are commonly called "cusps," in the speed-torque curve.

It follows from the above that the same conditions may be expected with the slotted-end-ring squirrel-cage construction. It also seems that the increased apparent leakage mentioned in the paper, resulting in starting torque smaller than expected, may be explained partly by the character of the speed-torque curve with unbalanced secondary (see Fig. 7). Furthermore, since the field form of the rotor in axis ($A$ $A$) is materially different from that of the stator, appreciable differential or belt leakage has to be expected. Finally, there is some increased leakage around the end rings.

Fluctuations in primary current of twice slip frequency, as found by Mr. Weichsel, are also obtained in motors having unbalanced secondary phases. This effect, which again can best be demonstrated by reference to the extreme case, namely, a single-phase rotor, may be explained as follows: Consider the rotor running with a low slip. The single-phase currents in the rotor set up a pulsating field, which may be resolved into two fields rotating in opposite directions at a speed, relative to the rotor, corresponding to slip frequency. These two fields induce voltages in the primary of two different frequencies. One field rotates in the same direction as the rotor, adding the slip-frequency speed to the mechanical speed to induce a voltage of line frequency in the stator. The other field, rotating against the rotor, subtracts the slip-frequency speed from the mechanical speed $(1 - S)$, inducing in the stator a voltage of a frequency equal to the line frequency minus *twice* slip frequency. Thus, two voltages, differing from each other by twice slip frequency, are induced in the primary. In general, two voltages of nearly the same frequency acting on the same circuit produce variations, or "beats," in the current of a frequency equal to the difference in the two frequencies. In our case of a polyphase induction motor with single-phase or unbalanced secondaries, this "beat" frequency is twice the slip frequency, as explained above. These beats may or may not have a disturbing influence of practical importance on the line voltage. It is to be expected that in the majority of cases the influence is not of practical importance because wound-secondary motors are frequently operated with unbalanced secondaries without causing much disturbance.

Finally, attention may be called to the fact that the circle diagram does not give entirely correct results with unbalanced secondary, and therefore not with the cut end-ring construction either. The greater the unbalance of the secondary, the greater the discrepancy will be, and in the case under consideration it would appear that the greater the proportion of resistance in the end rings to the total rotor resistance, the greater the discrepancy should be. Referring once more to Fig. 6, it will be seen that the extreme case having all resistance in the end rings has very marked higher harmonics (see curve 5, for instance). It is not unlikely that such a condition may also bring about low-torque points, or cusps, at points other than the one above one-half synchronous speed.

**G. L. Hoard:** (by letter) This paper will not receive the attention which its excellence merits because the results of the investigation described are negative, that is, negative in the sense that the possibilities of the motor investigated are not very promising. This does not lessen the value of the paper, however. It is quite as important to know the limitations of a particular apparatus as to know its possibilities. The author is to be congratulated on the clear, concise manner in which the subject is presented.

As for the motor itself, it seems to give little promise in the way of improvement in induction-motor characteristics. Its only advantage apparently is an increased torque per ampere, but this advantage is much more than offset by the disadvantages of lower starting torque, lower breakdown torque, and lower maximum output. There is also one other possible disadvantage which is not mentioned in the paper. The heating in the rings is not uniform. The loss at section A of ring 2 in Fig. 6 will be considerably larger than at points near the cut in the ring. This is not likely to be a serious objection in a rotor structure, having the high thermal conductivity and good ventilation characteristics possessed by the squirrel cage. It would be objectionable, however, in any form of wound rotor. I should like to ask if there was any evidence of local heating in any of the tests run on the experimental motors?

**H. Weichsel:** Mr. Hoard pointed out that the heating in different sections of the rings must be different. This statement is correct. The current distribution in the different sections of the ring, determined by the method outlined in my paper, when plotted against time, is given in Fig. 8. It will be seen from the figure that the maximum heating occurs in the section A of Fig. 6 of my paper. Unfortunately, during the tests, no attention was paid to this phenomenon, which no doubt must exist.

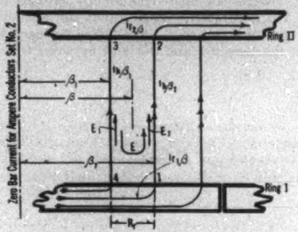


FIG. 8

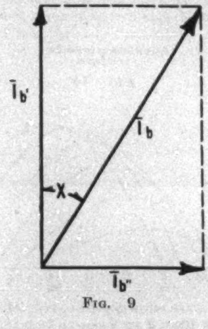


FIG. 9

In the discussion, references were made to the effect of non-insulated rotor bars. My experience has shown that in larger machines, even when a standard squirrel cage is used, quite appreciable currents flow during the starting period from the rotor bars into the laminations when the bars are not insulated. I know of instances where during the starting period very noticeable sparks occurred between the bars and the laminations. The heavy starting currents set the bars into vibration and, therefore, the contact between laminations and bar varied rapidly, and this resulted in quite visible sparks. If this condition exists in a standard squirrel cage, there is no doubt that the same condition exists in a much more pronounced manner in a squirrel cage with split rings.

Different discussors also have pointed out the similarity between a squirrel-cage rotor with split rings and a wire-wound armature with unbalanced resistance in the rotor. This similarity is correct. The tendency to a saddle formation in the speed-torque curve as pointed out by subsequent discussors doubtless exists in the machine with split rings in the same manner as in a machine with wire-wound armatures and unbalanced rotor resistances.

Mr. Hellmund referred to a point which is theoretically of greatest importance. He pointed out that the solution offered in my paper is based on the assumption that the current distribution in the bars follows a sine wave and that there is a possibility that this is not the distribution which actually exists in the bars.

In order to obtain an inside view of the actual distribution of currents in the bars, he applied the Kirchoff laws to a squirrel cage having only three bars per pole and determined for this structure the current distribution in the rings and the bars under the assumption that the e. m. fs. generated in the bars are of sine-shape distribution. This method of attack is perfectly correct, but I believe that the results obtained in this manner should not be generalized and applied to that problem of my paper, which deals with the current distribution in the squirrel-cage rotor having an infinite number of bars and split resistance rings.

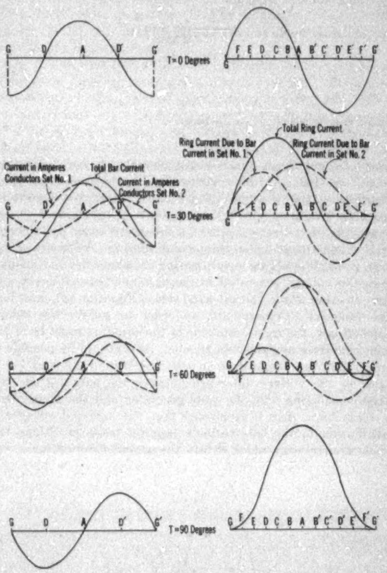


FIG. 10—BAR CURRENTS AND RING 2 CURRENTS

There is no doubt that the voltage generated in the bars due to the relative movement of the bars against a sine-shape rotating field must have a sine-shape distribution in space.

In my paper the first Kirchoff law, that the sum of all currents must be zero, has been fulfilled, as the whole problem was attacked by determining the ring currents by adding all the bar currents which flow into the ring.

Therefore, if it should be possible to prove that with the current distribution obtained in this manner, the voltage distribution along the bars and rings is such as to satisfy the second Kirchoff law, that is, "the sum of all voltages must be zero," it is evident that the assumed current distribution in the bars and the distribution in the rings as set forth in the paper is the actual distribution.

Let us consider a section of the squirrel cage as shown in Fig. 8 herewith. The distribution of the resultant current in the rings and bars is shown by arrows in agreement with the distribution found in my paper. For the local circuits, 1-2-3-4, we can write the second Kirchoff law in the following form:

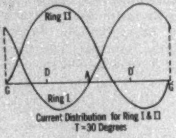


FIG. 11

$$E_2 - E_1 = E = i_{b_{\beta_2}} \cdot r_b - i_{b_{\beta_1}} \cdot r_b - i_{r_{2\beta}} \cdot R_r + i_{r_{1\beta}} \cdot R_r \quad (1)$$

which can be rewritten in the form:

$$(E_2 - E_1) - r_b\,(i_{b_{\beta_2}} - i_{b_{\beta_1}}) = R_r \left\{ i_{r_{1\beta}} - i_{r_{1\beta}} \right\} \quad (2)$$

where $E_1$ and $E_2$ are the voltages generated in bar 3-4, respectively bar 1-2. As the rotating field has a sine-shape space distribution, the voltages $E_2$ and $E_1$ must also have a sine-shaped space distribution. According to the assumption made in my paper, the bar currents, $i_b$, have a sine-shape space distribution. It is evident that under these conditions the difference of the e. m. f. which is left when subtracting the ohmic drop in the bars from the voltage generated in the bars must also follow a sine law—in other words, the left-hand side of Equation (2), must be a sine function. Consequently in order to satisfy the second Kirchoff law, the right-hand side of the equation must be of the same character as the left-hand side. If it should be possible to prove that the ohmic drop in the ring section 2-3 and 1-4 is equal to the voltage difference between the bars 1-2 and 3-4 when considering only the volts generated and the ohmic drop in these bars, then it is proved that the assumed sine-shape distribution in the bars actually requires potentials along the whole squirrel cage which satisfy the second Kirchoff laws.

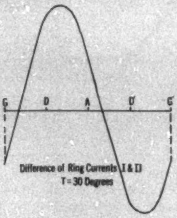


FIG. 12

If the bar current distribution in ampere conductor set No. 1 of the original paper follows a sine law as per:

$$i_{b_{\beta}}' = I_b' \cdot \cos\beta \quad (3)$$

where angle $\beta$ is measured from the point $G$ in Fig. 4 in the paper, then the ampere distribution in the ampere conductor set No. 2 follows the equation:

$$i_{b_{\beta}}'' = I_b'' \cdot \sin\beta \quad (4)$$

The resultant ampere distribution in the bars is given by equation:

$$i_b = I_b' \cos\beta + I_b'' \sin\beta \quad (5)$$

But the maximum bar currents $I_b'$ $x$ $I_b''$ for set No. 1, set No. 2, respectively are related to the maximum resultant bar current $I_b$ by equations:

$$I_b' = I_b \cos x \quad (6)$$

$$I_b'' = I_b \sin x \quad (7)$$

These two equations, (6) and (7), follow directly from the diagram Fig. 9 herewith, where $X$ is the time displacement of the resultant ampere conductors against the axis 0-1, which represents the time when the ampere conductors of set No. 1 are a maximum and set No. 2 are zero. Substituting (6) and (7) into (5), the resultant bar current is found to be:

$$i_{b_\beta} = I_b\,(\cos x \cos\beta + \sin x \sin\beta) \quad (8)$$

The same general law holds true for the voltages generated in the bars. The generated voltage minus the ohmic drop in the bars gives the "free voltage." This "free voltage" between the ends 2-3 of the bars 2-1 and 3-4 and between the ends 1-4 of the same bars must be equal to the ohmic drop appearing across these points due to the ring currents. As the bar currents as well as the generated bar voltages follow the same law, the "free voltage" which appears across the points 1-2 and 3-4 can be considered as the differential of Equation (8) when the latter is multiplied with a constant taking care of the ohmic drop. The potential difference referred to above is, therefore, given by:

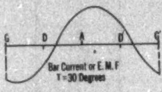


FIG. 13

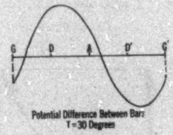


FIG. 14

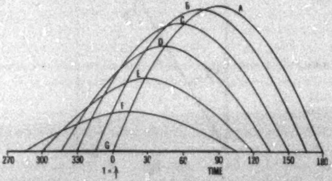


FIG. 15—CURVES SHOWING RELATIVE MAGNITUDES OF CURRENTS IN RING 2 AT VARIOUS INSTANCES OF TIME

$$d\,E = K\,(\sin x \cos\beta - \cos x \sin\beta)\,d\beta \quad (9)$$

The current flowing in ring No. 2 due to ampere-conductor set No. 1 is:

$$i_{r_{2\beta}}' = I_b \cos x \left( \frac{Z}{\tau} \right) \sin\beta \quad (10)$$

which follows from Equation (3) of the paper and Equation (6) of this discussion.

In the same manner the current in ring 2 due to ampere-conductor set 2 follows from Equation (**16**) of the paper and Equation (**7**) of the discussion:

$$i_{r_{2\beta}}'' = I_b \, . \, \frac{Z}{\pi} \sin x \, (1 - \cos \beta) \tag{11}$$

The resultant current in ring 2 is the sum of (**10**) and (**11**) and is given by:

$$i_{r_{2\beta}} = I_b \frac{Z}{\pi} \left\{ \sin x \, (1 - \cos \beta) + \cos x \sin \beta \right\} \tag{12}$$

In the same manner the resultant current in ring 1 is found to be:

$$i_{r_{1\beta}} = I_b \, . \, \frac{Z}{\pi} \left\{ \sin x \, (1 + \cos \beta) - \cos x \sin \beta \right\} \tag{13}$$

The difference between these currents gives:

$$i_{r_\beta} = 2 \, I_b \, . \, \frac{Z}{\pi} \left\{ \sin x \cos \beta - \cos x \sin \beta \right\} \tag{14}$$

This current multiplied by the ohmic resistance $R \, . \, d\beta$ for the infinitely small length of the ring coverd by an angle $d\beta$ gives Equation (**15**) for the ohmic drop in the rings over a section located at point $\beta$, that is, the ohmic drop of ring sections 2-3 and 1-4 of the rings 1 and 2.

$$= 2 \frac{Z}{\pi} I_b \left\{ \sin x \cos \beta - \cos x \sin \beta \right\} d\beta \tag{15}$$

It will be seen that this is exactly the same law as Equation (**9**), which represents the potential differences of points 2-3 and 1-4 due to the difference of generated voltage minus the ohmic drop for bars 1-2 and 3-4. Consequently the second Kirchoff law has been satisfied,—the sum of all the e. m. f. in the circuits 1-2 and 3-4 is zero. It has, therefore, been shown that for an infinite number of bars the assumption made in my paper of sine-shape current distribution in the bars is correct provided the rotating magnetic field has sine-shape distribution in space.

If, however, the number of bars becomes very small, then, as Mr. Hellmund has shown, the distribution of currents no longer follows a sine law. Experience with standard squirrel-cage rotors has shown that relations derived for an infinite number of bars give results close enough to be applied to a standard squirrel cage having a number of bars such as is usually found in practise, that is, approximately 10 or more bars per pole. It is justifiable to conclude that similar relations exist for squirrel cages with split rings.

The following is a brief description of a graphical solution:

Fig. 10 herewith shows for the time intervals $t = 0$, $t = 30$, $t = 60$, $t = 90$, the current distribution as determined in my paper for the bars and ring No. 2.

Fig. 11 herewith shows the current distribution as determined in my paper for rings 1 and 2 at a time $t = 30$ deg. The difference between these current distributions is given in Fig. 12 herewith, which is a sine-shaped curve and is 90 deg. displaced from the assumed current and voltage distribution of the bars shown by Fig. 13 herewith. But the potential difference between the ends of the bars due to the generated voltages and ohmic drop in the bars is the differential of curve Fig. 13 and follows a sine function as per Fig. 14, which is 90 deg. displaced against curve Fig. 13. Consequently it is co-phasal with the curve of Fig. 12. It follows that this graphical method leads to the same results found above by mathematics, that is, the current distribution as found in my paper for an infinitely large number of bars satisfies the Kirchoff laws.

# Excitation Systems
## Their Influence on Short Circuits and Maximum Power

BY R. E. DOHERTY*
Member, A. I. E. E.

*Synopsis.—Since 1920, when the general subject of excitation systems was reviewed at the White Sulphur Springs Convention, two important problems regarding these systems have arisen: One relates to the required excitation characteristics during system disturbances, and the other to the characteristics which are necessary in order to increase the maximum power above the steady state or static limit—i. e., in order to operate the synchronous machines under the condition of dynamic stability.*

*With respect to the former problem, the advantages and disadvantages of quick response excitation are considered. Such excitation tends, of course, to hold up the voltage during system disturbances, and is thus advantageous. However, it also increases the short-circuit current which circuit breakers must interrupt. The general trend in installing such systems is, therefore, in the direction of requiring larger circuit breakers. Such an excitation system is justified in many cases, and, indeed, it is essential in some. The extent to which the quickness of response and the maximum value of the excitation voltage are carried, is a question which, at present, should be settled by the conditions of the particular case.*

*As to increasing power limits, results are given which are very promising with respect not only to long distance transmission, but also to power systems which have approached the power limit as determined by the condition of present normal operation. A new regulator, unique in its operating characteristic, has been developed which makes it possible to sustain stable operation under the condition of dynamic stability, thus increasing the maximum power by taking advantage of a heretofore unexploited range of operation of synchronous machines. Comparative test results are given for different types of regulators. The new regulator alone showed extraordinary gain, giving an increase of maximum power from a steady state (steady-field excitation) value of 110 kw., to a maximum of 415 kw., on a system comprising a synchronous generator supplying power directly to a synchronous motor. This shows the extent of improvement obtainable in the machines themselves.*

*With an artificial 500-mile straightaway transmission line between the machines, a maximum power (received at the motor) equal to 90 per cent of the "infinite bus" value was obtained. The infinite bus value was 61 kw., 55 kw. was obtained, 44 kw. being the steady state power limit.*

*The excitation system, as controlled by the new regulator, provides a component of excitation voltage which is at all instants equal to the i r drop in the field circuit during the necessary small oscillation under dynamic stability. The i r drop is therefore compensated, the characteristic of the regulator being to introduce the effect of negative resistance. And with zero effective field resistance, the maximum power corresponds to the condition of constant flux linkages—the power under that condition is greatly increased above the constant field current value. This condition is approached by the new regulator.*

* * * * *

### INTRODUCTION

THE subject of excitation systems was reviewed comprehensively by several authors at the Summer Convention in 1920.[1–6] Interest has been renewed in this subject in the last few years by the new problems which have arisen in connection with power transmission. Two predominating facts have changed profoundly the general aspect of power transmission: One is the rapidly rising demand for increased reliability of service, and the other, the radical increase in the load per transmission circuit and in the specific loading of synchronous machines. And these facts have given rise to two corresponding problems in excitation systems. One related to the quick and adequate application of excitation voltage under the condition of sudden disturbances, such as short circuits, in order to reduce to a minimum the drop in line voltage—thus preventing to the greatest practicable extent the loss of load either from relay operation or from actual breakdown of motors or synchronous machines. The other relates to the possibility of increasing the maximum power above the generally recognized steady state or "static" limit—by operation under *dynamic* stability, that is, stability which depends upon motion. Instances: A spinning top, a staff balanced by a juggler, a bicycle in motion. Any tendency to fall gives rise to restoring forces. These may be inherent, as in the case of the top, or may be impressed by an external agency, as in the case of the staff or a slowly moving bicycle. But in either case the tendency to fall initiates the restoration. Moreover, in dynamic stability the play of these opposing forces is continuous. In the case of the synchronous machine operating under the condition of dynamic stability, the tendency to fall out of step initiates, through the voltage regulator, an appropriate change in excitation, thus providing the restoring forces. It is the purpose to discuss these two problems, and to report certain facts which appear to be steps forward in the solution.

Although the two problems are discussed separately, since in certain fundamental respects they are quite distinct, they are nevertheless related in the important respect that the problem of preserving continuity of service through periods of system disturbance would always be present, regardless of whether the system were normally operating under *static* stability or *dynamic* stability. However, it should be thoroughly appreciated that these two states of operation are fundamentally different, and that excitation systems which are satisfactory for the one may be altogether inadequate for the other.

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1. For all numerical references see Bibliography.

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With reference to the earlier work on excitation systems in connection with power transmission, two possible means for obtaining improved control of the excitation were suggested by the author at the Seattle Convention in 1925.[7] One was the use of a series exciter in the excitation circuit, in order to obtain immediate response in increased excitation voltage on the occasion of any sudden change in the electrical condition of the synchronous machine—in other words, to obtain an equivalent negative resistance in the field circuit. This, of course, would lengthen the duration of the transient, *i. e.*, tend to sustain the spontaneously increased alternator field current. The other suggestion was the use of a mercury arc rectifier as an adjunct in the excitation circuit. This would give immediate change in alternator field current in proportion to the change in armature current. Tests showed that with this scheme it was possible to operate above the steady state power limit. Further investigation has shown that there are equally effective and simpler means for both cases: One relates to the problem of short circuits, and the other to the problem of increasing the maximum power by operation under dynamic stability. These will now be considered.

## EXCITATION CONTROL DURING SYSTEM DISTURBANCES

The value of what has been termed "quick-response" or "high-speed" excitation, in connection with system disturbances, has been widely discussed.[8–12] There are, however, important points which warrant further emphasis. These relate to the rate of application of excitation, the maximum value of excitation voltage, the effect of this on short circuit currents, and also to the voltage regulator's role.

In the first place, what is quick-response excitation? When does the response of an exciter cease to be sluggish, and become quick? The term refers, of course, to exciters whose rates of magnetic build-up and build-down are higher than those ordinarily obtained with standard machines. The rates obtained with the latter over a wide range† are, say, from 15 or 20 volts per second to perhaps 250 volts per second in the case of 250 volt exciters, and half those values for 125 volt exciters, the range depending upon such factors as the volume (the $d^2 l$), and the speed of the exciter, saturation, character of the iron, etc. It would thus be somewhat venturesome to attempt to set a dividing line between high and low rates. However, anyone would probably agree that 25 volts per second is a low rate, and 1000 volts per second is a high rate. The width of the questionable zone depends, in the present state of definition, upon individual notions. But for the purpose of this discussion, we may very reasonably regard as quick-response excitation those cases where extraordinary means are employed to obtain rates of voltage change, both increase and decrease, unattainable in standard shunt or compound-wound exciters.

The extraordinary means referred to are, of course, familiar to all designing engineers, and include a number of schemes, such as special exciter design; the use of a series resistance in the shunt-field circuit, and impressing a correspondingly higher voltage; or, impressing a much higher voltage on the exciter field than corresponds, by Ohm's law, to the desired shunt-field current. Whether the latter, for instance, is accomplished by paralleling the field coils and impressing the given voltage, or by rewinding the coils for series connection, with the same amount of copper but with an appropriately smaller number of turns, and impressing the given voltage on the series circuit, the result is the same—namely, an accelerated voltage change. Such schemes for obtaining a high rate of d-c. voltage have been used for years,[13] ever since applications have been encountered which required a more rapid change in excitation voltage than could be obtained by standard machines. Quick-response excitation, as well as certain means of obtaining it, is not something which has recently come upon us as a new phenomenon.

Merely an additional application has arisen. If the line voltage drops, loaded motors may break down, the generators may fall out of step, and other disagreeable things may occur. If the drop in voltage takes place slowly, as occasioned, for instance, by a gradual application of load, the required rate of increase in excitation to prevent a critical dip in the voltage would be correspondingly low. However, if the drop is sudden—as produced by a partial short circuit—any possible advantage to be had from increasing the excitation voltage would be accomplished only by increasing it quickly. Thus, with the growth in the load per transmission circuit and, at the same time, a growing demand for greater reliability of service, it has become desirable and, in some cases, necessary to extend the use of quick-response excitation, formerly confined chiefly to special cases of industrial application in the field of large power transmission systems.

Published literature has brought out clearly the foregoing fact, that the quick application of excitation voltage on the occasion of a short circuit will decrease the chance of system breakdown—because it tends to hold the voltage up; but, as already mentioned, there are other important aspects of the subject which deserve further emphasis.

One of those aspects is that there are certain important details which are essential to an *effective* application of quick response excitation systems. The purpose being to reduce to a minimum the drop in voltage due to a sudden disturbance, it is clearly desirable for certain practical cases to have not merely a relatively rapid increase in excitation voltage, but the highest practicable rate and a relatively high value to which the excitation voltage can build up. For instance, a practical case of 250-volt normal excitation might require 5000 volts per second or higher, instead of 500, and a maximum value ("high ceiling") of say

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†Data in this connection will be given in a forthcoming paper in the *General Electric Review* by Mr. H. W. Washburn.

1000 volts, instead of 300 or 400. These points have been discussed by Mr. D. M. Jones in a recent issue of the *General Electric Review*.[12]

There are thus special applications in which, for optimum results, these features must be given due consideration.

But such features can be carried too far. The consequent increase in short-circuit current may create equally difficult problems. Indeed, the purpose of quick response excitation may be stated in terms of short-circuit current. Thus, reducing the voltage drop during the period of short circuit to a minimum, is equivalent to increasing to a maximum the value of the short-circuit current which the circuit breaker must open. Until the last few years the problem had been to reduce the short circuit current, but now, in these instances at least, the tendency is to increase it. In many cases this would not entail difficult switching problems, but there are some in which it would. Therefore, the suggestion is offered that the general trend has reversed to the direction of sustaining high short-circuit currents; and that in addition to both the proposed shorter time interval between the short circuit and the opening of the switch, and the radical increases in the generator capacity connected to a single bus, this is heading toward difficult switching conditions. Thus in the application of such excitation systems this general trend should be considered in true perspective.

The voltage regulator's place in this picture should be mentioned. So far as the particular function is concerned (of reducing the voltage drop during short circuit to a minimum), the *foremost* requirement of the regulator is that it should close its contacts immediately after short circuit, and keep them closed until the maximum desired excitation voltage appears across the field-collector rings of the synchronous machine; though there are other requirements, naturally. This fact, it seems, is generally recognized; and such commercial regulators generally are available. There are, however, other very important regulator functions and required characteristics which do not appear to be generally understood, particularly in connection with the problem of dynamic stability. These will be discussed later on.

To sum up the more important points regarding the influence of the excitation system during system disturbances: Quick-response excitation is highly desirable from the standpoint of reducing to a minimum the voltage drop during short circuit; and to this end, much higher rates and much higher values of excitation voltage are required, in certain practical cases, than had formerly been considered in quick-response systems. The definite present trend, however, in installing quick-response excitation systems is in the direction of increasing the duty on circuit breakers; and as a question of broad policy this should be fully considered. With respect to the voltage regulator, its foremost requirement in connection with short circuits is that it should promptly close the contacts and keep them closed until the desired d-c. voltage across the field-collector rings has been attained. Regulators which will do this generally are available.

### EXCITATION CONTROL FOR DYNAMIC STABILITY

Formerly, voltage regulation, line loss, and short circuits were the chief limitations considered in power transmission systems. During recent years another limitation, maximum power, has become very important. Under economic pressure, the load per transmission circuit has been increased until the maximum power which it is possible to transmit under existing conditions and practise, has been approached; indeed, in certain proposed power developments it has been exceeded. This has occasioned active investigation to increase the maximum power above the steady state, or static power limit.

Experience and early study regarding the possibilities in the design of the synchronous machine showed that although a gain in maximum power could be made in this way, it was nevertheless a moderate one, considering the economic limitations involved and the subject sought.[7] Even if such gains were made available—as they have been—there would, nevertheless, still remain in these machines the latent possibilities of increased maximum power beyond the static limit. And, as early studies indicated, it was these possibilities which could be rendered available by a proper excitation system. This view was presented at Seattle[7] in 1925, together with evidence that operation beyond the static limit could be obtained by proper excitation control.

With this fact established, intensive investigations were made of various forms of excitation systems with the object of increasing the gain and simplifying the circuits. Analysis and tests have definitely established three very important points. One point is that the factors of mechanical inertia, electrical transients, and damping afford a sufficient time element to make it possible to *sustain* operation under *dynamic* stability far beyond the *static* power limit. As discussed later on, the possibilities in this connection proved to be much more favorable than earlier investigation has indicated. The second point is the very essential part which the voltage regulator plays in this accomplishment. Third, the relatively low rates of change of excitation voltage at which it is possible, with proper regulation, to sustain dynamic stability. Although quick-response excitation may be desirable for many reasons, it is nevertheless a fact that it is possible to sustain dynamic stability with ordinary exciters, using proper regulation. These aspects will now be discussed in detail.

Consider the general nature of the phenomenon in question. It is a familiar fact that when a synchronous motor is supplied with power from a synchronous generator, either from a common bus or through an intervening reactance, there is a definite maximum power in either case, which can be transmitted at normal voltage under steady field conditions. Beyond this limit, generally referred to as the steady state or static power limit, the machines break apart.

It is also a fact that considerably more power can be transmitted by the same machines, over the same circuits, provided that the field excitation of the machines, instead of being held steady, is properly varied in accordance with the demands from moment to moment. Under this condition, as explained in Mr. Nickle's paper, the machines are, at each moment, either actually drifting further apart in phase with a consequent drop in voltage, or nearer together in phase with a consequent rise in voltage. That is, with a constant shaft load under such conditions of operation, there are sets of critical values of terminal voltage, field excitation, and space phase position, at which the electrical power input is just sufficient to supply the motor losses and the mechanical load; and on either side of this critical and sensitive balance, the tendency, *if the system were left to itself with no impressed change in field excitation*, would be either to fall apart with decreasing voltage and decreasing useful power input, or to fall close in phase with increasing voltage and increasing power input. Under these conditions the system is inherently unstable. But with proper control of the impressed excitation voltage, dynamic stability can be maintained, and the maximum power thus increased.

Now it is a well-known fact that the alternator field current tends inherently to adjust itself to maintain constant magnetic linkages in the field circuit.[7] This tendency is greater, the lower the resistance of that circuit; and in the limit, if the resistance were zero, the linkages would thus be maintained absolutely constant. Stated in other words, with zero resistance in the field circuit the effect of armature reaction on the field would be completely compensated.

The purposes of the mercury arc and the series exciter schemes, already referred to, are fully discussed in the literature.[7] The former effects partial compensation by changing the alternator field current in proportion to the line current, the latter, by introducing a component of excitation voltage which is at all moments proportional to field current, thus being, in effect, a negative resistance. With proper characteristics it should be possible in this way to introduce a negative resistance equal to the positive (*i. e.*, ohmic) resistance, and thus obtain the beneficial effects of zero resistance as discussed above. Although the series exciter has this advantage, it has some disadvantage in that it introduces an inductance (the exciting inductance of the exciter) in the external field circuit, thus increasing the transient reactance of the alternator and, therefore, decreasing the maximum power. Moreover, it would involve a somewhat complicated control. So, although both the mercury arc and the series exciter may yet find application in this connection, this investigation has shown that means are available which now appear much more promising.

The effect of negative resistance in the alternator field can be obtained by a special vibrating type regulator, actuated from the a-c. line voltage, and controlling an ordinary exciter. The inherent relationships between displacement angle, line voltage, field current, etc., during the necessary oscillatory motion in dynamic stability, are such that a component of excitation voltage proportional to the varying field current can be impressed by the above means, provided the regulator has proper characteristics. The above relationships are roughly indicated in Fig. 1. The oscillations may not be periodic; and the magnitude of variations would normally be less than indicated. But some oscillation must nevertheless be present in dynamic stability. The problem is to obtain an excitation system which will apply a voltage as shown as curve *d* in Fig. 1, that is, one which is in time phase with, and proportional to, the variable field current. It would thus constitute in effect a negative resistance. If the excitation voltage in this way were made equal to the *i r* drop at all instants, the objective of equivalent zero resistance would be attained.

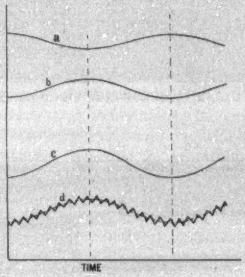


FIG. 1—PHASE RELATIONSHIPS DURING ANGULAR OSCILLATION OF AN ALTERNATOR

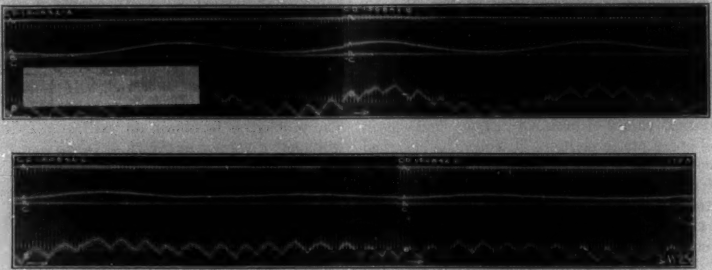
(a) Envelope of a-c. voltage
(b) Angular displacement
(c) Field current
(d) Exciter voltage

A regulator has been developed by Mr. C. A. Nickle which practically accomplishes this and, therefore, makes it possible to obtain large gains in maximum power above the steady-state limit: Its characteristics are referred to later, and are discussed in detail by Nickle and Carothers in a companion paper. Oscillograms of the line voltage, field current, and excitation voltage under dynamic stability are shown in Figs. 2A and 2B. (The record of field-current oscillations was magnified by inserting a constant d-c. component in the oscillograph circuit in opposition to that due to the field current.) In 2A a relatively large, damped oscillation is shown under the condition of operation at

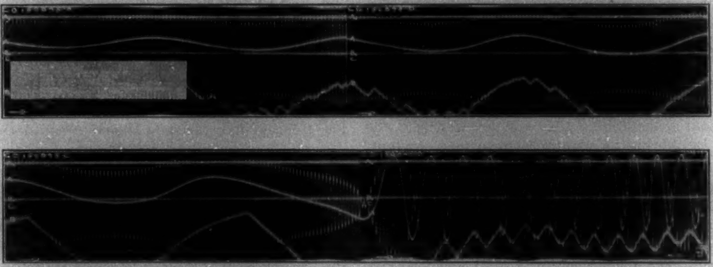
405 kw., the steady-state power limit being 110 kw. The test set-up is shown in Fig. 3. Fig. 2B shows a cumulative oscillation and breakout. In this case the power was only 370 kw., but the regulator was not adjusted at the optimum setting. The negative resistance was too large, thus introducing negative damping and consequent cumulative oscillation. But in both cases it will be noted that the variation of the average (that is, taking the average of the ripples) exciter voltage is substantially in phase with the field current variation; and hence a large component is exactly in phase, thus providing the effect of negative resistance.

But even if the terminal voltage variations are irregular, the regulator will cause the variation of the average exciter voltage to conform substantially to the same pattern, only reversed. That is, the exciter voltage will be up when the a-c. voltage is down, and vice versa. And since the field current variation is also of a similar, but reversed, form with respect to the a-c. voltage variation, it means that the exciter voltage will substantially follow the field current, even for irregular variations. Thus, in general, the effect of negative resistance is afforded by the regulator.

However, negative resistance is not an unmitigated advantage. It affords increased synchronizing power, but does so at the expense of positive damping. Damping due to the field winding is a very important factor in dynamic stability. As the effect of ohmic resistance is gradually eliminated by the foregoing means, the synchronizing torque is correspondingly increased,[17] but the net damping is decreased; and when the exciter voltage more than compensates the $i\,r$ drop, negative damping results. That is, under this condition any oscillation will cumulate and, unless other damping devices are present, will cause breakout. This is



(A) 405 Kw. Maximum Power Obtained with Adjustment of Regulator to Give Optimum Value of Equivalent Negative Resistance



(B) Cumulative Oscillation and Break-out at 370 Kw. Obtained with Regulator Adjustment to Give too Large Negative Resistance

Fig. 2—Oscillograms of Maximum Power with a Type A Regulator. Set-up Shown in Fig. 3. Steady State Power Limit, 110 Kw.

Curve A—$T\ S$ field current 1 mm = 0.3 amperes (true zero line displaced 50.5 mm. above reference line $B_O$) see text.
Curve B—Exciter armature voltage 1 mm. = 3.09 volts as measured from zero line $A_O$
Curve C—A. C. line voltage 1 mm. = 4.87 volts. P. T. Ratio = 20:1.

illustrated in Fig. 2B. The value of the negative resistance is fixed by regulator adjustment, as explained by Nickle and Carothers.

An amortisseur winding should thus be of some advantage when the machine is operating near the point of maximum power.

The phase relations of the various components of excitation voltage should be further considered. The period of oscillation is of the order of 1 sec.—*i. e.*, of a frequency of one cycle per second. Since $\frac{L}{R}$ of the field for this condition is of the order of 2 to 3 sec., $\frac{X}{R}$ at one cycle per second would be of the order of 12 to 18. It follows that the alternating component of field current due to the pulsating exciter voltage will lag by approximately 90 deg. Hence, referring to Fig. 1, we may say for the purpose of rough illustration that that component of alternating exciter voltage which is in phase with the given alternating component of field current (in phase with the angular position), produces a component of field current and, therefore, a torque, in time quadrature. This torque is thus in phase with the motion and is, therefore, negative damping, tending to increase the motion. It opposes the positive damping represented by the alternating component of $i\,r$ drop, and when it is in excess of the latter, cumulative oscillations follow.

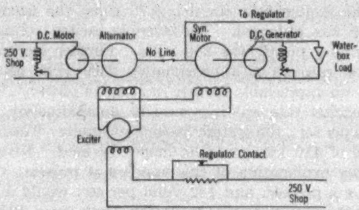


FIG. 3—TEST SET-UP WITHOUT TRANSMISSION LINE

Machine Ratings
Alternator and motor TS-6-435-1200-4000/2300 volts
D-c. motor and generator MPC-6-300-1200-250/275 volts
Exciter MP-4-17-700-250 volt 68 amperes
Synchronous reactance (without saturation) of generator = 46 ohms
$W\,R^2$ of rotor (total) = 2880 lb-ft.$^2$

The other component of exciter voltage which is in time quadrature with the field current, produces a component of field current in phase opposition to the given field current. It thus decreases the synchronizing torque.

The foregoing relations are of course not strictly true, but they will serve to illustrate the general nature of the effect of impressing different components of excitation voltage, and to show how regulators with different operating characteristics may produce very different results of maximum power and stability.

The point of view of evaluating the effect of the exciter and regulator in terms of equivalent circuit constants in the field can be developed further. As already explained, that component of exciter voltage which is in phase with the field current gives the effect of negative resistance. Now the component which is in time quadrature (lagging), gives the effect of an inductance in the circuit—*i. e.*, equivalent to increasing the transient reactance. This component is undesirable, at least so far as the maximum power is concerned. It follows that a component in phase opposition to the latter would give the effect of negative reactance, and would thus be advantageous.

With the new regulator, which impresses an exciter voltage in phase opposition with the line voltage variation, and therefore in phase with the field current variation, operation under dynamic stability was carried far beyond the steady state or static power limit—in one particular test among many, under the set-up of Fig. 3, to over 4 times the static limit, *i. e.*, to 450 kw.

Digressing for a moment in retrospect, the author's view regarding one aspect of this problem has changed. In the earlier stages of this general investigation[7–14] when a study was being made to find means for compensating the effects of armature reaction on the field, it appeared that any scheme involving a vibrating regulator actuated by the a-c. voltage, and controlling an exciter, would be too sluggish, and that therefore some other scheme, such as the mercury arc and series exciter, would be necessary. Subsequent investigations, however, have shown that on account of the inherent character of the relationships between the line voltage, angle, and field current, as shown in Figs. 1 and 2, the excitation voltage rate does not have to be extremely high in order to effect such a compensation. Taking advantage of the time element afforded by inertia and damping, the average exciter voltage can be made to vary, up and down, in time phase opposition with the line voltage variation, and, therefore, approximately in time phase with the field current—provided the regulator gives prompt and appropriate response in excitation voltage. In other words, more can be accomplished by a vibrating regulator than had been anticipated in the early stages of the investigation.

The foregoing discussion has centered largely about the regulator and the alternator characteristics. It may be asked, what effect has the exciter voltage build-up rate upon the maximum power which can be transmitted under dynamic stability?[16] Such operation obviously depends in a decisive way both upon the characteristics of automatic voltage regulators, and the quickness of response of the excitation source. An excitation *system* is a composite, and not a number of independent elements. An exciter can obviously do no more than react, in accordance with its inherent characteristics, to the conditions which are imposed upon it by the regulator and the connected circuits;

while the regulator can only control the particular exciter, whatever it may be, according to the regulator's inherent characteristics, and as it is influenced by the controlling and controlled circuits. An excitation system is thus like most other systems—if all components are not properly constituted and coordinated, it will not function efficiently.

It happens, however, that the exciter voltage rates obtainable from standard exciters are high enough to sustain dynamic stability, as shown under the heading, TESTS. The range of rates of voltage build-up of standard exciters has been given under EXCITATION CONTROL DURING SYSTEM DISTURBANCES. This does not mean that quick-response excitation should not be used if its use is desirable for some other reason—say to apply excitation quickly on the occasion of a system disturbance. If the regulator has the right characteristics, it can apply quick-response excitation as readily as it can apply the excitation from standard exciters, and obtain the same maximum power, as shown later.

A very definite distinction, however, must be drawn between the rate of variation, up and down, of exciter voltage as the contacts close and open, on the one hand, and the consequent rate at which the average excitation voltage changes, on the other. This difference may be very great depending upon the type of regulator.

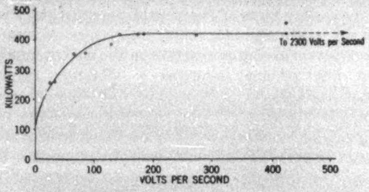


FIG. 4—MAXIMUM POWER AS A FUNCTION OF THE EXCITER VOLTAGE BUILD-UP RATE, FOR THE TEST SET-UP OF FIG. 3, USING TYPE A REGULATOR

The question regarding the relative influence of regulators and of the voltage rate of exciters on the maximum power which can be transmitted under dynamic stability will now be answered by tests.

## TESTS

One particular test set-up, among a large number, is shown in Fig. 3, including the ratings of the machines. The tests were run at about half voltage in order not to overload the d-c. generators under the condition of the large increase in power. Even at half voltage on the synchronous machines, the d-c. output (normal voltage) at maximum power was more than normal. The alternator fields were wound for 250-volt excitation. The exciter was a 250-volt machine, operating at 50 volts at zero power, 200 volts at the ultimate maximum power—*i. e.*, at 415 kw., (Fig. 4).

There are four principal voltage regulators with which comprehensive maximum power tests were made, including tests at different exciter voltage rates. Others were tested, but not so comprehensively. The four types are:

A. Original model of the regulator embodying the new principle. This will be referred to as type *A* in the following discussion.

B. New commercial form embodying, in the main, the characteristic features of the original model. This will be referred to as type *B*.

C. Older commercial form with d-c. coil, which will be designated as type *C*.

D. The usual commercial form without d-c. coil, which will be designated as type *D*.

In tests with type *A* regulator and with an exciter voltage build-up rate of 24 volts per sec. (as measured by oscillograph at the exciter terminals under the actual condition of maximum power), a value of power equal to twice the fixed-field, or steady-state value, was obtained; and with a measured build-up rate of 142 volts per sec., (obtained by changing connections in the exciter field circuit), 3.75 times the fixed-field value was obtained. The average exciter voltage at maximum power was 200 volts. Further increase in exciter rate up to approximately 2300 volts per sec. gave no appreciable further increase in power. When the exciter rate was increased to approximately 3000 volts per sec., the system became unstable. The maximum of 415 kw. could no longer be held. No satisfactory explanation of this appears at present. Now 24 volts per sec. and 142 volts per sec. would not be termed quick-response excitation, even on a 125-volt exciter; but here it was a 250-volt exciter. Thus, those rates would correspond to 12 volts per sec. and 71 volts per sec. on a 125-volt exciter. It was the most sluggish exciter which had been found.

The only interpretation which the author has been able to make of those facts is that the regulator played a decisive part in obtaining the improvement in power limits, and that quick-response excitation had nothing to do with it, because quick-response excitation was not used in obtaining the results; and moreover because, when the rate of exciter build-up was increased to a high rate, no further improvement was found. Fig. 4 shows the curve relating the measured exciter voltage rate and maximum power, as obtained in the test set-up of Fig. 3.* The build-down rate was of the same order as the build-up rate. A different series of tests on the same apparatus, but showing about 5 per cent greater maximum power is shown by Nickle and Carothers. A more detailed reference will be made later to the exciter build-up rate and its relation to maximum power.

Another test under the conditions of Fig. 3 was taken, using type *B* regulator. The maximum power obtained was 385 kw., *i. e.*, 3.5 times the steady-state limit; and hunting did not begin until a load of 250 kw. was passed.

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*This may answer satisfactorily the question raised in the literature, reference 16.

The test set-up shown in Fig. 5 includes an artificial 500-mile transmission line between the motor and generator, the reactance of the line being approximately 1.5 times the synchronous reactance (46 ohms) of the generator, the generator and motor being duplicate machines. The machines were each regulated at 2240 volts. In this case, the static power limit was 44 kw., the infinite bus value being 61 kw. With the type *A* regulator, 55 kw. was transmitted, *i. e.*, received at the motor. This is 90 per cent of the infinite-bus value. This result was obtained with two different exciter rates, namely, 500 and 250 volts per second. The average exciter voltage at the maximum power was 66 volts.

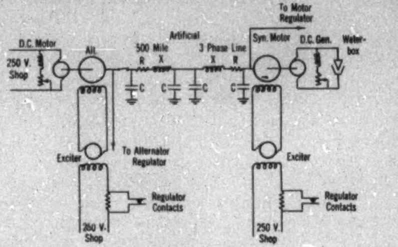

FIG. 5—TEST SET-UP WITH ARTIFICIAL 500 MILE TRANSMISSION LINE

Machine ratings
Alternator and motor TS-6-435-1200-4000/2300 volts
D. C. motor and generator MPC-6-300-1200-250/275 volts
Exciters MP-4-17-700-250 volts
$X = 35.5$ ohms
$R = 5.0$ ohms
$C = 3.75$ mf.

The increase in maximum power was naturally less here than in the case of Fig. 3, because the line impedance drop is, in a sense, an unregulated factor in the situation; that is, since the voltage is regulated at the machine terminals, the machine impedance drops only are corrected. For instance, if the voltage at the middle of the line, instead of at the ends, were regulated at normal value, the increase in power would be much greater. The voltage at the machine terminals would then be greater, since in that case the line reactance would in a sense be equivalent to an addition to the synchronous reactance under the condition of Fig. 3.

Referring again to the tests, a number of regulators has been tried in various factory tests using the same machines and circuits. None of the former commercial models in these comparative tests could approach the maximum power obtainable under dynamic stability with the new model. In certain early factory tests with 5-kv-a. machines, the new regulator alone (type *A*, and type *B*) made possible a decisive increase in maximum power above the steady-state limit. The maximum power obtained with these types was 11.0 kw., the steady-state limit being approximately 7.0 kw.,† and the infinite-bus value, calculated, was 12 kw. With the other regulators, including types *C* and *D*, and also a commutator type, the synchronous machines broke apart at substantially the steady-state limit of power.

In later tests, however, in which larger machines, with relatively larger inertia and damping, were used, it was possible with commercial regulators to obtain an increase above the steady-state limit. In the tests of Fig. 3 (no impedance between machines), in which the new regulator type *A* gave 3.75 times that limit, with practically no hunting until 3.5 was passed, type *D* without d-c. coil gave only 1.75 to 2.0 times that limit with serious hunting. In the latter case, hunting began as soon as the steady-state limit was passed, in spite of the most favorable adjustment, and became progressively worse with increase in load, hunting out of step at the above values of power. With the new commercial regulator type *B*, however, hunting began at about 2.5, and at this value the stability was comparable with that of the commercial type *D* just after passing the steady-state limit, *i. e.*, at 1.0. In the case of the older commercial type with d-c. coil, (type *C*), only a small increase was obtained. The machines hunted out of step soon after steady state was passed. Fig. 6 shows the results for all four cases, giving the maximum power which could be held in synchronism. Fig. 7 gives the same results with an indication of the extent and character of hunting.

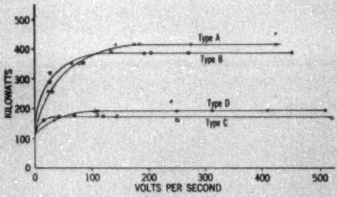

FIG. 6—MAXIMUM POWER AS A FUNCTION OF THE EXCITER VOLTAGE BUILD-UP RATE FOR THE TEST SET-UP OF FIG. 3, USING THE DIFFERENT TYPES OF REGULATORS

Dynamic stability can be sustained also by hand juggling of the exciter rheostats. With rheostats and field-circuit connections such that the exciter rate would be 500 volts per sec. if all resistance were suddenly cut-out, it was possible to sustain over twice the steady-state value of power by hand control of the rheostats. Watching the line voltmeter, the field rheostat was shifted back and forth to correct for the changing voltage. When the voltage started to decrease, the rheostat was set by guess at a point to correct the decrease; and as it began to increase, a similar correction was made. It is to be noted that the rheostat was not all cut-out, and all cut-in, as with a regulator; instead, the change in resistance was relatively small. Hence the actual rate of exciter voltage was correspondingly small. Even so, it was possible to obtain an increase of 100 per cent above the steady-state limit by hand juggling.

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†These results are given by Messrs. Nickle and Carothers. The test set-up involved two duplicate synchronous machines connected through a line reactance equal to two-thirds of the synchronous reactance of either machine.

### REGULATOR CHARACTERISTICS

The above results are very interesting in view of the parallel drawn by Messrs. Nickle and Carothers, between such hand control and the inherent action of a regulator—such as the commercial type $D$ referred to—which operates on the principle that a definite ratio (time closed) ÷ (time open) exists for each value of a-c. voltage. Thus, these authors show that for small changes in the average exciter voltage, the effective exciter voltage rate from the one voltage to the other is not the rate corresponding to the closed contact, as might at first be supposed, but a much smaller rate—corresponding, much as in hand control, to the relatively small shift from one resistance to another. A small drop in a-c. voltage merely changes the ratio (time closed) to (time open) on the regulator corresponding to the new average resistance necessary for regulation; and the average exciter voltage changes according to a correspondingly slow transient, and not according to the total exciter rate. For illustration, if the above ratio does not change at all, the exciter voltage varies up and down at full exciter rate, but the average value does not change; and if the ratio does change, following a small change in a-c. voltage, it merely sets a new average resistance, *i. e.*, a setting for a new average exciter voltage. But the latter reaches the new value by a relatively slow transient corresponding not to the rate with contacts closed, but merely to the change in average resistance. This is true, in that range of a-c. voltage variation in which the regulator functions normally—*i. e.*, in which the contacts vibrate. This is of the order of ± 10 per cent. If, for instance, the voltage falls below the lower critical value, the contacts close and stay closed; in which case the total exciter rate is the effective rate. But this condition does not exist in operation under dynamic stability. It is thus somewhat analogous to hand juggling, and it is therefore not surprising that the maximum power obtained in test in the two cases was about the same.

The type $A$ regulator, however, operates on an entirely different principle—a principle which no other regulator has embodied; and this explains why the increase in maximum power is much greater when it controls the voltage. The principle is: *for a given change in a-c. voltage, the new average exciter voltage for the new condition is reached at a continuous voltage rate equal to the actual total rate of the exciter. This is initiated promptly, and is true for all a-c. voltage changes, small as well as large.** Other regulators may initiate their response promptly, and, moreover, the effective excitation voltage rate may be equal to the rate of the total exciter voltage for *large* changes in a-c. voltage. But no other regulator, to the author's knowledge, affords this equality of voltage rates for relatively small changes in a-c. voltage—such, for instance, as would be encountered normally under the condition we have been considering, namely, dynamic stability. Operating according to the above principle, the new regulator thus causes the average exciter voltage to keep pace with the alternator field current, as in Fig. 1, and therefore provides the effect of negative resistance. (The value of negative resistance is proportional to the resistance in the d-c. coil of the regulator, as explained by Nickle and Carothers. It can thus be easily adjusted for the optimum condition.)

The circumstance that makes it possible for the exciter voltage to follow the field current so closely is that the variations of the latter are relatively slow (of the order of one cycle per second—and this is roughly true for power systems in general) and are also relatively small. For numerical illustration, if the amplitude of variation were, say 10 per cent, of the average field current (which would be a relatively high variation), this would mean that, for complete resistance compensation, the average exciter voltage must vary 10 per cent, and in phase. And the required rate of exciter voltage change would be,

$$\frac{d\,e}{d\,t} = \omega\, e_0 \cos\,(\omega\, t + \alpha)$$

where the voltage $e_0$ is the amplitude of the variation, and $\omega$ the corresponding angular velocity. If the amplitude $e_0$ is 10 per cent—*i e.*, total variation of ± 10 per cent—and the frequency is one cycle per second, the maximum rate (during the cycle) of the average excitation voltage is,

$\omega\, e_0 = 2\,\pi \times 10$ per cent $= 62.8$ per cent of the steady component per second.

Hence, assuming that the exciter is operating at 80 per cent of the rated voltage of say 250 volts, the maximum voltage rate would be roughly

$$0.62 \times 0.8 \times 250 = 124 \text{ volts/sec.}$$

This, of course, would be the lowest permissible value of the maximum rate under the assumptions. It will be noted that this is of the order of the lowest voltage rate at which maximum power was attained—Fig. 4.

Thus, summing up the new regulator characteristics, it operates on a unique principle which makes it possible, on account of the relatively slow oscillation in dynamic stability, to impress an excitation voltage substantially in phase with the field current variations, therefore affording the effect of negative resistance, as illustrated in Fig. 2. It will be observed that the phase displacement between the field current and excitation voltage corresponds to only 2 cycles of a-c. voltage, *i. e.*, about 12 deg., since the cycle of variation corresponds to one second. In other words, the in-phase component is approximately 98 per cent of the total; the quadrature component, only 20 per cent.

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*For the detailed treatment of this, see companion paper by Nickle and Carothers, p.957.

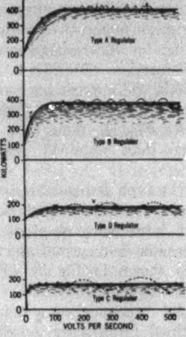

FIG. 7—THE SOLID CURVES ARE THE SAME AS THOSE SHOWN IN FIG. 6

The shading is intended to indicate the intensity and range of hunting. Thus heavy shading indicates serious hunting, and no shading indicates practically stable operation. The dotted line, with time as abscissa, indicates the general character of the oscillation corresponding to imminent break-out

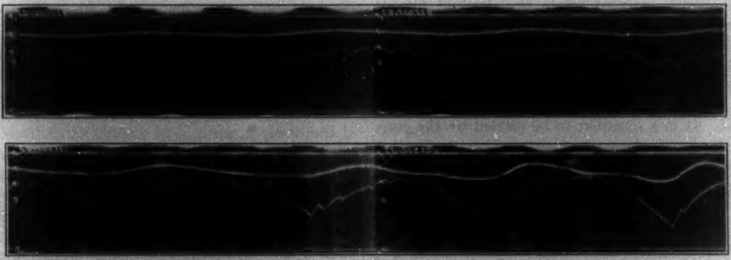

FIG. 8—OSCILLOGRAM OF MAXIMUM POWER TEST WITH A TYPE D REGULATOR ADJUSTED FOR OPTIMUM CONDITIONS. SET-UP SHOWN IN FIG. 3. STEADY STATE POWER LIMIT, 110 KW. 190 KW. MAXIMUM POWER OBTAINED

Curve A—Exciter armature voltage 1 mm. = 3.43 volts (as measured from zero line $A_O$)
Curve B—A-c. line voltage 1 mm. = 5 volts. P T. Ratio = 20:1
Curve C—*T S* field current 1 mm. = 0.135 amperes (true zero line displaced 0.09 mm. above reference line $C_O$)

Now consider the type *D* regulator in these terms. From the principle of its operation, already discussed, it is clear that for a given change in a-c. voltage, a new setting of average resistance, corresponding to the new, anticipated average excitation voltage, is instantly effected, and a transient of the average excitation voltage is started, the rate of the transient depending upon the magnitude of the change. For a small change the rate is very low; for a large change, it approaches the full exciter voltage rate. Hence in an oscillation, and especially a small oscillation, in that range of the voltage variation in which the voltage is changing only slightly, as immediately after the maximum or the minimum, practically no change in the average excitation voltage occurs. And as the variation reaches the larger slopes, the excitation voltage begins to change more rapidly. This means inherently a lag in phase. Thus, unlike the type *A* regulator, here the effect of the regulator and exciter, instead of being a negative resistance, is equivalent to shunting the resistance of the alternator field circuit by an inductance. For any spontaneous change in the field current, the *i r* drop, due to the added current, is present in the first moment, but gradually disappears as the current is taken by the shunt inductance which has no resistance; and the rate at which the *i r* drop disappears depends upon the magnitude of the change in the alternator field current. This therefore represents the conditions as outlined for the type *D* regulator. Thus, the exciter voltage is represented by the voltage across the parallel circuit of the inductance and resistance. As such, it must be out of phase with the total current. Fig. 8 shows the actual phase relations under a test in which the conditions were the same as those in Fig. 2, except the type *D* regulator was used instead of the type *A*. It will be noted that the phase displacement between the average excitation voltage and the alternator field current corresponds to about 10 cycles—*i. e.*, about 60 deg. lag. Thus, only 50 per cent is in phase, 86 per cent in quadrature (lagging). This explains why only 190 kw. could be obtained instead of 405 kw. in Fig. 2. Fig. 8 shows the conditions at the maximum power, just preceding break-out. The regulator was adjusted at its optimum setting.

In the case of type *C*, since it also is not so responsive to small voltage changes, it naturally must also permit large angular and voltage oscillations, just as soon as the dynamic state of operation is entered; and thus the increase in maximum power should also be less than that of the types *A* and *B*, and the hunting more severe. And this is what actually happens, as indicated in Fig. 7. While this regulator serves well the general purpose for which it was designed and for which it has been and is being widely used, it is nevertheless seriously handicapped—even somewhat more than the type *D*—in connection with operation under dynamic stability. For this state of operation, a new regulator with a new principle of operation is required, such as types *A* and *B*.

### SUMMARY AND INTERPRETATION OF CONCLUSIONS

What interpretation is to be placed on the foregoing discussion and facts? Should quick-response excitation systems be always used, and how "quick" should the response be? What element in the excitation system has made possible the large gains in maximum power reported in the paper? What is the significance of the gains regarding the future of power transmission?

Two predominating facts in the field of power transmission have changed the aspect of this subject, and have introduced two corresponding problems in excitation systems. The growing demand for increased reliability of service has required quicker response of excitation systems on the occasion of system disturbance, in order to reduce the voltage drop to a minimum. And the increase in the load per transmission circuit, and in the specific loading of synchronous machines, has brought rather sharply to the fore the limit of maximum power, which formerly was encountered only infrequently.

Quick-response excitation is of distinct advantage in important power systems where the demand for increased reliability of service is pressing; and this, of course, includes many of them. The character of the excitation system—whether of moderately rapid voltage rate, or an extremely rapid rate together with a high "ceiling" voltage—is, to a large degree, a matter of economics. It is a question to be settled by the conditions of the particular case.

But the question involves the very important aspect of increased short circuit current. The use of quick response excitation means, in general, larger switches. The general trend in this direction should be duly considered in the choice of an excitation system.

Radical increase in maximum power above the steady-state limit—*i. e.*, above the value of maximum power which has heretofore been the practical limit—has been obtained in test. This involves a state of operation which is fundamentally different in character from that of the usual present day power system. This state of operation is termed *dynamic* stability, as distinguished from the condition of steady state, or *static* stability.

The increase in maximum power has been made possible by a new and unique voltage regulator. The principle which distinguishes this regulator, designated in the paper by "type *A*", from all other existing types is this: *for a given change in a-c. voltage, the new average exciter voltage for the new condition is reached at a continuous voltage rate equal to the actual total rate of the exciter. This is initiated promptly, and is true for all a-c. voltage changes, small as well as large.* The effect of the type *A*, or of type *B* which operates on the same principle, is to provide an equivalent negative resistance, thus giving a maximum power corresponding to constant flux linkages in the alternating field circuit. In other words, it gives a component of variable excitation voltage which is at all moments equal to the $i\,r$ drop, thus compensating for the resistance—and therefore for the armature reaction. See Fig. 2. This made it possible to obtain in test a maximum power of 415 kw. on a system, Fig. 3, for which the steady-state limit was 110 kw. See Fig. 4. This is a much greater maximum power than obtained with any other regulator.

The effect of the type *D* regulator is equivalent to shunting the resistance of the field circuit with an inductance, thus introducing a phase displacement between the alternator field current and the excitation voltage. This is shown in Fig. 8. The maximum power is therefore less, being 190 kw., as compared with 415 kw., since the resistance cannot be completely compensated without introducing the effect of inductance. See Fig. 7.

For relatively large changes in a-c. voltage—say of the order of 10 per cent above, or 10 per cent below—the rate of the effective d-c. voltage approaches the total exciter rate with contacts closed; and for still larger changes in a-c. voltage, as in the case of a short circuit, the contacts close and stay closed, thus giving the full exciter rate. This type is thus appropriate for a normal regulator below the steady-state limit, or in the case of short circuits; but it is not so suitable for quickly regulating for small voltage changes, as required under dynamic stability.

The type *C* regulator also delays action, on account of the dashpot, until large angular oscillations are set up; and its consequent effect is equivalent to inserting an inductance shunt around the resistance, as in the case of type *D*. Hence the maximum power is also lower and the hunting is more severe than in the case of types *A* and *B*.

All other commercial types, such as the "face plate regulator" and its derivatives, and the commutator type, are still more sluggish for small voltage changes. Some of these types are efficacious for quickly changing excitation on the occasion of short circuits, but they are not appropriate for sustained operation under dynamic stability. Thus, the difference between the large increases in maximum power which have been obtained by using the new regulator, type *A*, as reported in the paper, and the increases obtained by other regulators and by hand control, is explained by the fact that the new regulator functions according to an entirely different and novel characteristic, which was chosen with respect to the particular requirements of this problem.

Quick-response exciters are not essential to operation under dynamic stability. An increase of 100 per cent in power above the steady-state limit was obtained with the type *A* regulator controlling an exciter voltage rate of 24 volts sec. on a 250 volt exciter; and an increase of 275 per cent, with a rate of 142 volts/sec. No further increase was obtained when the exciter voltage rate was further increased, even to 2300 volts/sec. Thus quick-response excitation gave no more maximum power than the low rates of ordinary exciters. But it gave as much —*i. e.*, it did not impair the results, until the high rate of 3000 volts/sec. was reached. (Where an extremely high exciter voltage rate is used in connection with short circuits, this rate is applied only on the occasion of a short circuit. Normally it is not in the circuit.) Then instability occurred. It is thus concluded that quick-response excitation was not essential to the maximum gain in power limit obtained in the tests, because the gain was made without the use of such excitation.

But this does not mean that such an excitation system may not be desirable in a system normally operated under dynamic stability. It surely would be desirable, but for another reason—namely, to reduce the voltage drop during system disturbances, which is also the reason it is used on present systems normally operating below the steady-state limit.

It should be added that the type *A* and type *B* regulators possess the required characteristics for controlling excitation both under dynamic stability and under the condition of system disturbances such as short circuits. That is, they possess characteristics suitable for general application.

The most important aspect of the results is the possible influence on the future of power transmission. There are two phases of this which should be considered. One relates to the possible increase in the output of the synchronous machines for large central stations, or in special cases of industrial plants where momentary demands of power are greater than could be carried under steady state operation, the other, to long distance transmission.

With respect to increasing the output of synchronous machines, the foremost limitations in design formerly were heating and voltage regulation. The latter was practically removed by the advent of the automatic voltage regulator, and the former has been progressively raised, principally by improvements in ventilation, and by the reduction of energy losses—*i. e.*, sources of heat. Consequently, the rated output has gradually approached, and has finally reached the immediate range of maximum power. Thus a new limitation is encountered. Although one cannot draw general conclusions from factory tests, yet from both the test results and theoretical considerations, there appears to be no reason at this time why the limitation of maximum power could not be set much higher by the proper use of the new regulator, thus making possible a continued progress in higher specific loading of synchronous machines. The prospects are still more hopeful for satisfactory application in those special cases where considerable momentary overload is required from time to time. And even if normal operation were to be below the steady-state limit, less safety margin would be required, since the system would be capable of operating above the steady-state limit. That is, a new margin may thus be created by the regulator.

As to long distance transmission, the results appear very promising. With the new regulator, a maximum power equal to 90 per cent of the infinite bus value was obtained over an artificial 500 mile straightaway line. The economic limitations in the power projects involving long transmission distances have been widely discussed in the literature. The situation has been faced that the maximum power which could be transmitted over very long distances was not sufficient to justify the necessary investment. The results of the present investigation are promising with respect to the possibility of removing some of those limitations and thus placing such projects on a much more attractive basis. Future developments will show whether such hopes are justified.

There is another factor which appears to be favorable in considering the application of the regulator on large machines. In such machines the mechanical inertia is relatively greater, and the electrical transients inherently longer than in the small machines used in this investigation. Thus, it would appear that the regulator would operate under still more favorable conditions when controlling the larger machines.

## ACKNOWLEDGMENTS

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## Discussion

For discussion of this paper see page 969.

# Automatic Voltage Regulators

## Application to Power Transmission Systems

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WITHIN a relatively short time conditions in transmission systems, as regards continuity of service, and maximum power, have radically changed. A few years ago, the amount of power transmitted over important lines was relatively small compared with their ultimate transmitting capacity. In such cases, the systems were inherently stable, and there was a reasonable margin of power with respect to load swings and short circuits. Automatic voltage regulators were used at that time chiefly for maintaining more uniform voltage conditions than could be obtained by intermittent adjustment by hand control. Different types of regulators for this purpose have given satisfactory service for a number of years. However, conditions have gradually changed. Within the last few years the power to be transmitted has increased to such an extent that it has now become necessary to consider means seriously for increasing the maximum power and for insuring continuity of service during transient disturbances, such as load swings and short circuits. The object of this paper is to present the results of an extended investigation along these lines. A new regulator is described which will accomplish the above purposes, and the theoretical analysis is confirmed by test results.

### FACTORS INFLUENCING POWER LIMITS

In order to facilitate an understanding of the principles involved and the functions of voltage regulators and exciters in a transmission system, some of the factors which determine the power limit of a system will be considered briefly. When the shaft load of a synchronous motor connected to an alternator, directly or through a transmission line, is gradually increased, a point is soon reached where no more electrical power can be supplied to the motor. The amount of power which can be thus supplied depends upon the total reactance between the generator and motor, including their internal reactances, and upon the values of excitation which exist. Small values of excitation give small values of breakdown power, and large values give large values of breakdown power.

The magnitudes of the excitation which can be applied to the machines are limited by the condition that certain predetermined terminal voltages shall not be exceeded. For different sets of fixed excitation values there will be corresponding values of terminal voltages and power when breakdown occurs. Under these conditions of fixed field excitation, the maximum power obtained is termed the steady state or static power limit for those terminal voltages. For instance, if the power on a given system is 100,000 kw. when the machines pull apart, and if the terminal voltage is 220,000 volts at this instant, all excitations being held constant, then 100,000 kw. is the steady-state power limit for operation at 220,000 volts.

Under proper conditions of variable excitation it is possible, however, to operate beyond this limit. The first experimental evidence that this was practicable was obtained[2] by the use of devices which increased the excitation as a function of load current, and thus compensated for armature reaction simultaneously with its occurrence. While recognizing the advantage of such factors as mechanical inertia, damping, and electromagnetic transients in stabilizing operation during system disturbances, earlier investigation, including tests with existing standard commercial regulators, had nevertheless not brought out the full possibility of utilizing these factors in producing stable operation above the steady-state limit. Indeed they definitely showed that even if it were possible to hold the machines in synchronism significantly above that limit, this was accompanied by prohibitive hunting. Later investigation, however, showed that stable operation beyond the steady-state limit was possible with control by a vibrating contact regulator having special and unique characteristics. This will be fully discussed later.

### DYNAMIC STABILITY

When operating below the steady-state power limit, machines are inherently stable, *i. e.*, with no changes in the electrical constants, certain increments of shaft power may be applied without loss of synchronism, and the machines are thus considered to be in static equilibrium. For values of transmitted power above the static power limit, conditions are radically different.

Although equilibrium may exist for certain values of excitation, power, angular displacement, etc., nevertheless, if the excitations remain constant, any increase in shaft load increases the angular displacement with a resultant decrease in transmitted power. Thus, for this condition, the rate of change of power with respect to angular displacement is negative, and any change in shaft load produces cumulative action. Fortunately, due to inertia of the moving parts, the damping action of short-circuited rotor windings, and the tendency of the flux linking the field winding to remain constant,

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[1] Both of General Electric Co., Schenectady, N. Y.

*Presented at the Regional Meeting of the A. I. E. E., St. Louis, Mo., March 7-9, 1928.*

[2] Nickle and Lawton, *An Investigation of Transmission System Power Limits*, TRANS. A. I. E. E., 1926, Vol. XLV, p. 12.

the process of falling out of step is relatively slow; and if the excitations are properly adjusted following a change in shaft power, the machines can be held in equilibrium.

Similarly, when a decrease in shaft power occurs, the angular displacement decreases with a resultant increase in transmitted power. For conditions of fixed excitation, the machines will thus continue to approach each other in phase position, and will come to equilibrium at a smaller angle for which the machines are inherently stable.

Dynamic stability may be further illustrated by considering the equations of the simple case of two identical cylindrical rotor machines, connected directly together electrically.

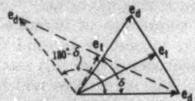

Fig. 1—Vector Diagram for Two Identical Cylindrical Rotor Machines on the Same Bus

The power as a function of the excitations or nominal voltages (assumed to be the same on both machines) and the angular displacement between the rotors, is[3]

$$P = \frac{e_d^2}{x} \sin \delta \qquad (1)$$

where

$e_d$ = nominal voltage corresponding to the excitations on the generator and motor.

$x$ = total reactance of both machines.

$\delta$ = the angular displacement between the rotors.

From this relation, it may be seen that the same power may be transmitted at two values of $\delta$, *i. e.*, one angle $\delta'$ less than 90 deg., and another angle (180 deg. $- \delta'$) greater than 90 deg., for given values of excitation and reactance. The vector diagram is as shown in Fig. 1. From this figure, it is evident that the terminal voltage is different for these two operating angles and is given by the equation

$$e_t = e_d \cos \frac{\delta}{2} \qquad (2)$$

From the standpoint of power transmitted, it is thus immaterial whether operation occurs at $\delta'$, less than 90 deg., or at 180 deg. $- \delta'$, greater than 90 deg., for given values of nominal voltage. However, the terminal voltage will be less in the latter case, the comparison being cos (90 deg. $- \delta'/2$) or sin $\delta'/2$, with cos $\delta'/2$. Therefore if the terminal voltage is to be the same, we must operate at greater excitations at 180 deg. $- \delta'$ than at $\delta'$ and consequently more power can be delivered.

It is considerably more difficult to maintain equilibrium at 180 deg. $- \delta'$ than at $\delta'$ since the rate of change of power with angular displacement is negative and the machines are in a state of dynamic balance. Any increase in shaft power will cause breakdown if the excitations are not changed, and any decrease in shaft power will cause the angular displacement to revert to the inherently stable angular displacement, $\delta'$, with a resultant abnormal rise of terminal voltage.

Operation above the static power limit thus necessitates a continually varying excitation. What appears at the present time to be the most suitable means for properly controlling these excitations is an automatic voltage regulator of suitable design.

### Automatic Voltage Regulators

Automatic voltage regulators are of two general types, *i. e.*, the rheostatic type and the vibrating contact regulator. The characteristics of different regulators of the same general type may be essentially different, depending upon the constructional features and methods of control.

Before the introduction of automatic voltage regulators, voltage was controlled by hand adjustment of rheostats in the field circuits of the exciter or alternator. Such control is necessarily rather intermittent and it is evident that a regulator designed to perform the same functions as hand control, but more continuously, would materially improve voltage conditions. The rheostatic type functions in this way, and for certain conditions of operation gives quite satisfactory service.

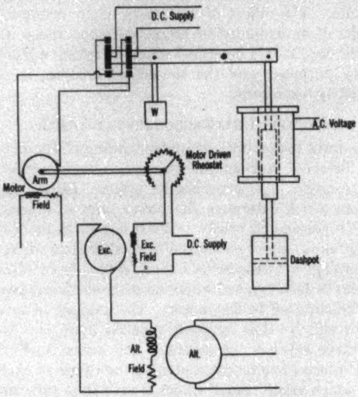

Fig. 2—Schematic Diagram of an Excitation System Controlled by a Rheostatic Type Regulator

This type of automatic regulator in its simplest form consists of a motor driven rheostat, the motor being controlled by relays operated from the voltage which is to be regulated. Fig. 2 gives a schematic diagram of a regulator of this type. When the voltage rises above a predetermined value, the relay connected to the regulated voltage impresses a voltage on the armature circuit of the motor, and the resistance of the motor driven rheostat is gradually increased until the regulated voltage is again normal. Similarly, when the controlled voltage decreases, the relays reverse the voltage impressed on the motor armature, thus causing the resistance of the motor driven rheostat to decrease until the regulated voltage has increased to normal value. When the regulated voltage is normal, the contacts are all open and the motor driven rheostat becomes stationary in that position which will just hold normal voltage for the particular load conditions which exist.

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[3] Doherty and Nickle, *Synchronous Machines*, Trans. A. I. E. E., 1926, Vol. XLV, p. 927.

This regulator in its simplest form is rather sluggish in action, being merely an improvement over intermittent hand control, and is not adapted for taking care of sudden disturbances, such as short circuits, or for controlling voltage when machines are operating above the static power limit. However, this regulator may be modified in a simple manner to take effective care of short circuits occurring when machines are operating below the static power limit.

When a short circuit occurs, there is a sudden abnormal drop in terminal voltage which seriously reduces the synchronizing power of the synchronous apparatus for given values of excitation, angular displacement, etc. At such times it is essential that the excitations be increased as rapidly as possible to prevent the machines breaking from synchronism. It may also be desirable to decrease the excitation rapidly when short circuits are cleared in order that the system shall not be subjected to abnormal rises of terminal voltage. These rapid changes of excitation during short-circuit conditions may be obtained by means of auxiliary relays, one of which short circuits the motor driven rheostat at such times as the resistance is being decreased, *i. e.*, immediately following a drop in terminal voltage; and another relay which inserts a normally short-circuited resistance in the exciter field circuit at such times as the resistance of the motor driven rheostat is being increased, *i. e.*, immediately following a voltage rise.

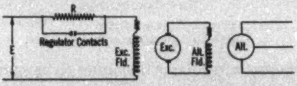

FIG. 3—SCHEMATIC DIAGRAM OF AN EXCITATION SYSTEM CONTROLLED BY VIBRATING CONTACTS

One of the advantages of such a regulator lies in the fact that, by suitable design, the entire regulator may be stationary for relatively long periods of time during steady load conditions, resulting in quietness of operation. The ratio of the time that the rheostat is in motion to the time that it is stationary is largely determined by the voltage sensitivity of the controlling relay. The greater the sensitivity of this relay, the smaller will be the voltage change required to operate the contacts and the motor driven rheostat will be in motion a larger part of the time. With extreme sensitivity, the relays and motor driven rheostat would be in operation all the time and the regulator would be essentially a vibrating contact regulator. The sensitivity of this relay has an important effect upon the possibility of such a regulator controlling operation above the static power limit.

When machines are operating above the static power limit, they are continually in the incipient stage of breakdown. As they begin to break from synchronism, the terminal voltage changes are small, but if these small changes of terminal voltage are not corrected, the machines soon obtain sufficient velocity of separation to make it extremely difficult to restore them to equilibrium at a later instant, regardless of the speed of build-up of the excitation voltage. In order that such a regulator may respond to these small voltage changes, the controlling relay must be made very sensitive to small voltage changes with the result that the regulator will be in operation at all times, even for power transmission below the static power limit. One of the advantages of this regulator is then lost, *i. e.*, still operation over relatively long intervals of time, and it becomes essentially a vibrating contact regulator.

A characteristic common to all vibrating contact voltage regulators is that the amount of excitation is controlled by periodically short circuiting a resistance in the excitation circuit as shown in the simple diagram in Fig. 3.

When the contacts are closed all the time, maximum voltage is obtained at the exciter terminals, and when open all the time, minimum voltage is obtained. By varying the ratio of the time that the contacts are closed to the time that they are open, any value of average exciter voltage between these limits can be obtained.

There are different ways by which a vibrating contact regulator can change the average exciter voltage from one value to another. One method is to close the contacts at once and keep them closed until the desired exciter voltage is reached, vibration then being resumed at the proper ratio of time-closed to time-open to maintain this new exciter voltage.

Another way would be to change suddenly the ratio of time-closed to time-open to a value which will ultimately sustain the new value of exciter voltage. It might seem that, since the ratio of time-closed to time-open is changed suddenly to a new definite value, the new average exciter voltage is immediately obtained. This, however, is not the case, the new average exciter voltage being obtained only after a relatively long transient. The equations for this transient are derived in the Appendix.

Although, in both cases, steps are taken at once to increase the average exciter voltage, nevertheless there is a marked difference in the time required to attain this new value. When the contacts close and remain closed until the new average exciter voltage is reached, the exciter voltage builds up at the inherent magnetic rate of the exciter, and, as a function of time, will appear as in Fig. 4. It is evident that for this case, the maximum voltage rate possible is obtained from a given excitation system.

When the ratio of time-closed to time-open is merely changed from one value to another, *normal vibration of the contacts is not momentarily interrupted*, and the transient appears as shown in Fig. 5.

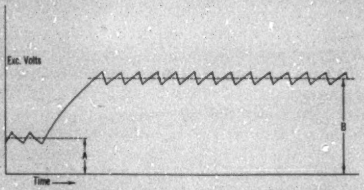

Fig. 4—Variation of Exciter Voltage as a Function of Time for the Case of a Sudden Drop of Alternator Voltage

Contacts close and stay closed until the new value of exciter voltage is reached

The difference in time required for a given change of exciter voltage can be readily appreciated by inspection of Figs. 4 and 5. As seen from Fig. 5, any regulator which operates on the principle of suddenly changing the ratio of the time-closed to the time-open of the contacts, causes the rate of change of average exciter voltage to be very seriously reduced below its inherent or maximum rate, and is seriously handicapped for operation under conditions of dynamic stability. In other words, such a principle used in a scheme of voltage regulation makes the effective voltage rate of the exciter much lower than the possible rate which might be obtained.

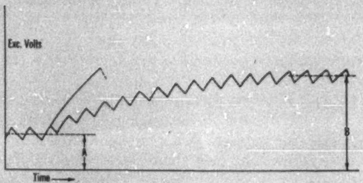

Fig. 5—Variation of Exciter Voltage as a Function of Time for the Case of a Sudden Drop of Alternator Voltage, When the Ratio of Time-Closed to Time-Open of the Contacts Suddenly Changes

Oscillographic verification of the curves shown in Figs. 4 and 5 are shown in Figs. 6 and 7. In making these tests to determine the effect on the exciter voltage of a sudden small reduction in the a-c. voltage, a separate source of voltage, not controlled by the regulator, was impressed on the control coils. The relays of the regulator controlled the terminal voltage of an exciter in the usual way and the oscillograms were taken of the variation in exciter terminal voltage when the amplitude of the impressed voltage was suddenly decreased.

The difference in effective exciter voltage rate for the two cases, particularly for very small changes of impressed voltage, is so marked that a regulator operating on the first principle can effectively control machines in stable operation far above the static power limit, whereas a regulator operating on the principle of suddenly changing the ratio of time-closed to time-open of the relay contacts, gives about the same results as good hand control.

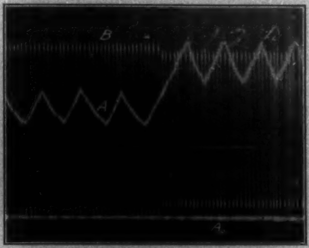

Fig. 6—Oscillographic Verification of Fig. 3, Using New Regulator

Curve A: Exciter voltage
Curve B: Alternator voltage

Consider the simple regulator shown in Fig. 8. The voltage which is to be regulated is impressed on coil *A* which is arranged to pull upward on its plunger. One end of this plunger is mechanically connected to the dashpot *B* and the other end is attached to the pivoted lever *C*. This entire lever system is adjusted by means of the weight *W* so that it is statically balanced when normal regulated voltage is impressed on coil *A*.

Fig. 7—Oscillographic Verification of Fig. 4, Using Regulator Without D-c. Coil

Curve A: Exciter voltage
Curve B: Alternator voltage

The lever system on the left comprises a coil *D*, connected to the armature terminals of the exciter, a plunger which is pulled downward by coil *D* and a pivoted lever *E*. The motion of this lever is opposed by the spring *F*. The contacts *G*, when closed, operate relays which short-circuit resistance in the exciter field circuit and, when open, insert this resistance. For simplicity, the contacts *G* are shown in the diagram to perform this function without the use of auxiliary relays.

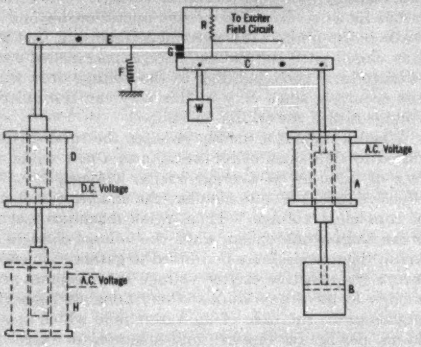

FIG. 8—SCHEMATIC DIAGRAM OF A VOLTAGE REGULATOR OF THE VIBRATING CONTACT TYPE

Assuming that the voltage impressed on coil *A* is normal, and that the lever *C* is in a given position as shown, then when the contacts are closed the resistance *R* in the exciter field circuit is short circuited and the exciter voltage increases exponentially. As it increases, the pull of coil *D* also increases and eventually becomes great enough to overcome the opposing pull of the spring, and the contacts open. The resistance *R* is thus inserted in the exciter field circuit, the exciter voltage decreases, the pull of coil *D* decreases and eventually, the spring overcomes the pull of coil *D* and the contacts close again. These operations then continue periodically at a frequency of the order of five cycles per sec. The exciter voltage then consists of periodic exponential increases and decreases as shown in Fig. 9. If the average value of this exciter voltage is just sufficient to maintain normal voltage on the alternator, the regulator is in equilibrium and lever *C* remains in the assumed position. If now a drop of alternator voltage occurs, lever *C* is no longer in equilibrium and starts to rotate in a clockwise direction. As the left end gradually rises, more and more average exciter voltage is required to balance the pull of the spring. Lever *C* will thus continue to move until the exciter voltage has increased once more to a value which will just maintain normal alternator voltage. The speed of motion is controlled by the dashpot which is necessary to give stable operation. Although the dashpot is necessary to stabilize the regulator, nevertheless it introduces sluggishness of response to changes of alternator voltage. The variation of exciter voltage immediately following a sudden drop of controlled voltage then appears as shown in Fig. 10. The effective speed of exciter build-up is then largely controlled by the characteristics of the dashpot. It is interesting to note that the dashpot causes the effective speed of build-up of exciter voltage to be modified in quite a similar manner as for a regulator which suddenly changes the ratio of time-closed to time-open following a drop in terminal voltage. The difference between the regulator described and one which suddenly changes its ratio of time-closed to time-open is thus more in degree than in principle, and neither type obtains marked increases of power above the static power limit.

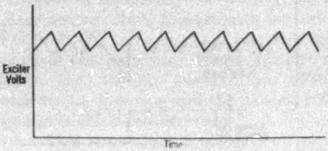

FIG. 9—VARIATION OF EXCITER VOLTAGE WITH TIME UNDER STEADY LOAD CONDITIONS

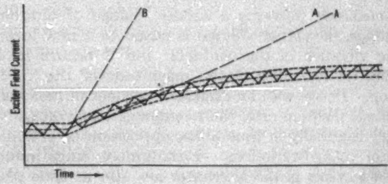

FIG. 10—CURVE SHOWING THE EFFECTIVE RATE OF CHANGE OF EXCITER FIELD CURRENT FOLLOWING A DROP OF ALTERNATOR VOLTAGE

a. Slope of Line A gives the initial rate of change when the ratio of time closed to time open of the contacts suddenly changes

b. Slope of Line B gives the rate of change when the contacts close and stay closed

When another coil *H* is added to the left hand lever system of the regulator described above, the regulated voltage being impressed on this coil, a distinct difference in operation occurs. As explained before, a definite average pull is required to overcome the force of the spring for any given position of the lever *C*. This pull is now made up of two components, one of which is a function of alternator voltage and another which is a function of exciter voltage. The exciter voltage, as before, controls the contact vibration and the total force due to both coils will appear as shown in Fig. 11. If the alternator voltage now suddenly decreases, the total pull also decreases and is no longer sufficient to overcome the counter pull of the spring and the contacts close and remain closed until an exciter voltage is obtained which, in conjunction with the reduced alternating voltage, is again sufficient to open the contacts. The characteristic of the regulator immediately following such a disturbance is as shown in Fig. 12. *Before the contacts can start vibrating again* the exciter voltage must increase to a new definite value, the magnitude of the change depending upon the magnitude of the drop of alternating voltage. Thus, immediately following a sudden change of alternator voltage, the exciter voltage is raised to a new level in one vibration of the contacts; and it occurs in one vibration regardless of the magnitude of the voltage drop. Hence, with an excitation system of reasonable voltage build-up rate, the average exciter voltage will vary essentially in time phase opposition to the alternator voltage variations. Furthermore, since induced field currents in the alternator are also in time phase opposition to the voltage variations, it follows that this excitation system furnishes exciter voltage changes in time phase with the alternator field current variation and thus compensates all or part of the *i r* drop in the field circuit. In other words, the effect is obtained of introducing negative resistance in the alternator field circuit. This phenomenon is discussed in detail in a companion paper by Mr. R. E. Doherty.

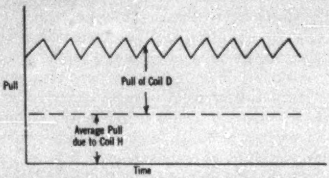

Fig. 11—Magnetic Pull on Lever *E* of Fig. 8 as a Function of Time Under Steady Load Conditions

The actual magnitude of the change of exciter voltage for a given change of alternating voltage may be controlled by suitable choice of the relative strengths of the coils *D* and *H*. The greater the strength of coil *H* compared with that of coil *D*, the greater will be the percentage increase of exciter voltage for a given change of alternator voltage.

It may be noted that the left hand lever system alone can never restore the regulated voltage to normal, although it can be made as nearly so as desired by controlling the relative strengths of the two coils. This is evident from the fact that if the voltage was restored to normal, the total pull required to open the contacts would be the same as its initial value, that is, the exciter voltage would be unchanged, but, by assumption, there is a drop in a-c. voltage for this exciter voltage. Hence the left hand lever alone cannot completely restore normal voltage. The final adjustment of voltage to normal is accomplished by the relatively slow movement of lever *C*.

## Some Requirements for Dynamic Stability

When machines are operating under conditions of dynamic stability, they are continuously beginning to fall out of step or to approach each other in phase position with resultant voltage variations which are at first of small magnitude. Any delay of the regulator response to these voltage changes at this time has a vital effect upon the performance of the system. However, the fact that a voltage regulator closes its contacts immediately following a drop of voltage, or vice versa, is not alone sufficient to permit operation beyond the static power limit. It is extremely important that they stay closed until the exciter voltage has reached a new average level corresponding to the voltage drop which has occurred, since only in this way can the inherent voltage rate of the exciter be utilized.

When a regulator merely changes the ratio of time-closed to time-open of its contacts to a new value, the rate of build-up of average exciter voltage, *i. e.*, the effective rate, becomes smaller, the smaller the change of controlled voltage. Thus, when machines start to break from synchronism, when the voltage changes are small, the machines are permitted to gather momentum before the effective exciter voltage rate becomes great enough to be of any value. Conditions are somewhat analogous to the case of an automobile which travels 20-mi. per hr. for one hr., and attempts to travel the next 20-mi. at such a speed as to average 40-mi. per hr. for the entire distance. It cannot be done.

It is also important that the controlled exciter shall have a sufficient inherent voltage rate so that a call for increased or decreased exciter voltage by the regulator is promptly followed by the change. The impulse to change the exciter voltage, although given instantly, is of little value if the exciter cannot respond.

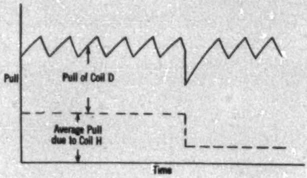

Fig. 12—Magnetic Pull on Lever *E* of Fig. 8, as a Function of Time, When the Alternator Voltage Suddenly Decreases

It should be noted, however, that sufficiently rapid response of exciter voltage does not necessarily require abnormal exciter voltage rates. Important gains in maximum power have been obtained with the most sluggish exciters obtainable when used in conjunction with a regulator of the proper characteristics. There are several factors, discussed later, which exert a decided influence on the requirements of exciter voltage rate for any given case.

Another requirement for dynamic stability is that the voltage regulator shall not cumulate such oscillations as might occur. Transmission systems, comprising synchronous machines, are ordinarily oscillatory, *i. e.*, when shaft loads are suddenly changed, the system does not arrive at its final position of equilibrium at once, but only after an oscillation. Once such an oscillation begins it may be either cumulated or damped out, depending upon the time phase characteristics of the regulator and excitation system. The proper time phase relations are obtained largely by the mechanical design of the regulator and the use of anti-hunting devices as have been used in the past.

The characteristics of an automatic voltage regulator and other elements of the excitation system do not alone determine the amount of power which can be transmitted over a system operating under dynamic stability. There are other important system characteristics which have a powerful influence on what a regulator and excitation system can accomplish in the way of increased maximum power.

One of these is the mechanical inertia of the rotating parts. The problem alone of operating above the static power limit would present much less difficulty if all machines had exceedingly large values of inertia. In this case, variations of shaft loads would produce such small values of acceleration that the changes in angular position, and therefore changes in terminal voltage, would be very slow—so slow that practically any kind of voltage regulation, including hand control, could maintain the voltages normal at all times and the maximum power would have the same value as for the case of infinite busses.

This may be illustrated by considering the analogous case of balancing on one's hand, a rod with a weight on the upper end. As the distance of the weight from the point of support is increased, the torque, for a given angular displacement from the vertical, is increased in direct proportion, but the moment of inertia is increased as the square of the distance. Hence, for any angular displacement, the angular acceleration is inversely proportional to the distance, and the necessity for very rapid response of the hand decreases. It is this difference which makes it so much more difficult to balance a toothpick than a ten-ft. rod.

Now in the case of synchronous machines, with finite values of inertia it is more difficult to maintain dynamic equilibrium; and with no inertia at all, it would be extremely difficult with practical regulators and excitation systems if other factors were not present.

One of the most important of these is damping. When machines drift apart in phase position, the terminal voltage also shifts and there is relative motion between the rotating fluxes in the machines and the rotor windings. This relative movement causes currents to be induced in the short circuited rotor windings and a torque arises which has a component proportional to this relative velocity at a given instant. Such a torque constitutes damping and causes the drift out of synchronism to occur more sluggishly than if it were not present. Increased damping action thus permits more time for the excitation system to function, and dynamic stability is thus more readily maintained.

Still another important factor exists, namely, the electromagnetic inertia of the field windings. As machines change their relative phase position, the armature current changes and tends to increase or decrease the flux linking the main field winding, depending on the nature of the current change. This change in flux linking the field winding is not instantaneous, but occurs exponentially with time, its rate of change depending on the constants of the field circuit. Thus, due to the electromagnetic inertia of the field circuit, the inherent tendency is for the field current to change spontaneously in the right direction to increase stability.

Considering the limiting case of zero resistance, the flux linking the field circuit could never change without changing the impressed voltage, and any regulator could obtain a maximum power corresponding to conditions of constant flux linking the field winding instead of constant current, *i. e.*, transient reactance would be effective for conditions where synchronous reactance is now effective.

An approach toward conditions of constant flux linkages in the field circuit can be made in different ways. Either a decrease of resistance or an increase of inductance will tend toward constant flux linkages. When this result is obtained by reducing the resistance, the transient reactance is unchanged and an increased time constant is obtained without harmful results. However, if inductance were inserted in the field circuit, the increase in transient reactance more than offsets the benefits gained by the increased time constant. For infinite inductance in the field circuit, synchronous reactance is effective at all times, since conditions of constant field current would then exist. The maximum power would then be the static power limit, by definition.

Any one of these factors, described above, may make it possible to operate machines above their static power limit. It so occurs, however, that even with all three available, the full advantage of their combined effect cannot be utilized in increasing the maximum power unless a more effective control of the excitation is available than has been in the past. In order to use these factors to the greatest advantage, a new regulator, with the features already described, has been designed. With this regulator, decisive increases in maximum power have been obtained in test. These are also given in a companion paper by Mr. R. E. Doherty.

## EFFECT OF CONSTANTS OF THE FIELD CIRCUIT

It has been pointed out that damping and electromagnetic inertia make operation under conditions of dynamic stability more easily obtained. When the resistance of the field circuit is increased, the damping torque for given values of slip, and the time constant of the field circuit, are both decreased. It would then be expected that, for a given excitation system, the maximum power would be decreased when resistance is inserted in the field circuit.

The insertion of external inductance in the field circuit, *i. e.*, increasing the leakage and transient reactances, also influences maximum power. Although field inductance increases the tendency toward constant flux linkages in the field circuit by increasing the time constant, nevertheless it also increases transient reactance which more than offsets the benefits of the increased time constant. For infinite reactance, constant field current would exist and, as already mentioned, the dynamic power limit would be identical with the static power limit.

These effects of resistance and inductance in the field circuit on maximum power have been verified by tests and the results are shown in Fig. 13.

Although it is true that the effect of increased field resistance may be counteracted by changing the regulator characteristic[4], nevertheless, it introduces more difficulties in regulator design. Furthermore, inherently low resistance, as far as it is economically obtainable, is to be preferred to artificial low resistance.

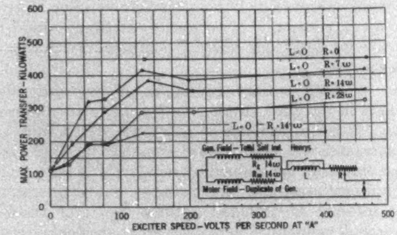

FIG. 13—RELATION BETWEEN MAXIMUM POWER AND EXCITER VOLTAGE RATE FOR DIFFERENT VALUES OF RESISTANCE AND INDUCTANCE IN THE ALTERNATOR FIELD CIRCUITS

Circuit connections as shown in Fig. 16

## SHORT CIRCUITS

Sudden disturbances, such as short circuits, result in a sudden drop in terminal voltage with a resultant loss of considerable synchronizing power for given conditions of angular displacement, fluxes, field currents, etc. Hence, at the instant a short circuit occurs, the angular displacement between the various machines begins to change and sufficient momentum may soon be acquired to cause loss of synchronism if corrective measures are not taken at once and as rapidly as possible.

Just as in the case of dynamic stability, inherent damping, inertia, and the tendency toward constant air-gap flux are favorable, their general effect being to increase the time required for breakdown to occur after a short circuit and in some cases they may, acting alone, prevent breakdown from occurring at all, if the short circuit is cleared in a reasonable time. In general, more time is permitted for excitation changes when these factors are large than when they are small.

However, such favorable factors as do exist do not seem to be sufficiently effective to allow the use of exciter voltage rates available in standard exciters, although these rates are sufficient for dynamic stability. This point is fully discussed in the companion paper by Mr. R. E. Doherty. As pointed out in that paper, the requirements of an excitation system to take care of short circuits are that the change of exciter voltage be initiated at once, and that it increase at a very rapid rate to the value which has been determined by the conditions of the particular case.

To fulfil the above requirements, the regulator must promptly close its contacts and keep them closed until the proper excitation voltage is reached, and the exciter voltage rate must be relatively high. Moreover, the regulator must not distinguish between phases—*i. e.*, it must act the same way regardless of the phase on which the short circuit occurs. Regulators which will accomplish this are commercially available.

If the a-c. voltage change is non-symmetrical, *i. e.*, different on the different phases, as in the case of single-phase short circuits, the response of a regulator controlled from one phase only will be different, depending upon the phase to which it is connected. In order that the regulator action shall be the same, regardless of the phase which is short circuited, various schemes are available. One of them provides an actuating a-c. voltage for the regulator which is proportional to the positive phase sequence component of the 3-phase line voltage. Another scheme, which is very effective, is to replace the usual a-c. voltage coil of the regulator in Fig. 8 by a small polyphase stationary torque motor, the shaft of which replaces the pivot of the right hand lever. A dead short circuit on any phase then causes the torque of this motor to become zero, and therefore maximum effectiveness in increasing the exciter voltage is obtained.

## TEST RESULTS

During the last few years, much valuable information has been obtained and many question have been answered by extensive factory tests, and also field tests. The latter will appear in a forthcoming paper. The first tests, in which the new regulator was used, were made on small 3.75 kw. machines with an interconnecting transmission line. The motor and generator were identical, each having a direct synchronous reactance 1.55 and a quadrature reactance 0.30 on the basis of 10 kv-a. at 100 volts, line to line. On this same basis, the reactance of the interconnecting line was 1.0 and the resistance was 0.05. The diagram of connections for this system is shown in Fig. 14. A shunt motor drove a synchronous generator which delivered power over a transmission line to a synchronous motor. This motor drove a shunt generator which could be loaded by means of a resistance across its terminals. The excitation was furnished by a 3-kw., 1800-rev. per min., 125-volt shunt wound exciter. During these tests self excitation and separate excitation with different voltages impressed on the field circuit of the exciter were used. In this way, exciter voltage rates ranging from 50 to 400 volts per sec. could be obtained.

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[4] As has been pointed out, a new regulator is available which has the effective characteristic of introducing negative resistance in the field circuit, the value of this negative resistance depending on the regulator constants.

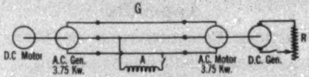

FIG. 14—SCHEMATIC DIAGRAM OF THE SMALL TRANSMISSION SYSTEM USED IN THE TESTS

The first tests on this system were to determine the static power limit. For various values of fixed excitation on the motor and generator, power-voltage curves were taken and the results are shown in Fig. 15. From the locus of maximum power points, the static power limit for any operating voltage may be determined. The operating voltage used throughout these tests was 110 volts, giving a static power limit of 6.1 kw. The maximum power of the line alone, *i. e.*, with infinite busses at each end, is neglecting resistance 12.0 kw.

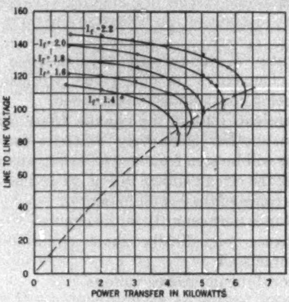

FIG. 15—POWER-VOLTAGE CURVES BY CALCULATION AND TEST

Two AHI-4-3.75-1800-110-volt synchronous machines connected through a transmission line. Excitation on motor and generator held constant at different values

Tests were then made to determine the effect of exciter voltage rate on maximum power when commercial regulators, including both the types with d-c. coil and without d-c. coil, were used. The results showed that the maximum power was practically independent of exciter voltage rate for these regulators, the same power, *i. e.*, 7 kw., being obtained with various commercial regulators for widely different values of exciter voltage rate. It is interesting to note that this same value of power, slightly above the static power limit was also obtained by hand control. However, when the new regulator was used, the difference became apparent at once. The maximum power was increased immediately to 10 kw. and after careful adjustment this was increased to 11 kw., or a gain of approximately 60 per cent. When it is considered that the possible gain, assuming infinite busses at each end, is 70 per cent, the results are seen to contain elements of great practical importance.

The system was also shown to be remarkably stable to sudden shocks. A reactor, *A*, whose reactance was of such a value as to take a current of the order of normal current on the basis of 10 kv-a. at 100 volts, could be repeatedly connected across the terminals, and disconnected, and the system remained in synchronism, even when carrying a load of 9 kw. or 30 per cent more than standard regulators could obtain under steady conditions.

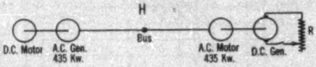

FIG. 16—DIAGRAM FOR LARGER TRANSMISSION SYSTEM USED IN TESTS

Machine Ratings:
Alternator and Motor: TS-435-1200-4000/2300 volts
D-c. Motor and Generator: MPC-6-300-1200-250/275 volts
Exciter: MP-4-17-700-250 volts—68 amperes

Question then arose concerning the difference that might be obtained using a larger system. Therefore another system, shown in Fig. 16, was set up, using machines having a rating of 435 kv-a. at normal voltage, *i. e.*, at 4000 volts. The synchronous reactance on this basis was 1.18 and the quadrature reactance was 0.62. For excitation purposes, a separately excited, 4-pole, 20 kw., 1200-rev. per min., 125-volt exciter was used in conjunction with various types of voltage regulators. During these tests, the machines were operated at reduced voltage, *i. e.*, 2200 volts, in order that the d-c. machines should not be too heavily overloaded. At this reduced voltage, the static power limit, as determined by power voltage curves taken under conditions of constant excitation, was 120 kw. With standard commercial regulators and with hand control, a maximum power of 180 kw. was obtained, this power being practically independent of the exciter voltage rate. The new regulator increased this power to 480 kw., approximately an increase of 170 per cent, *i. e.*, the maximum power was almost tripled.

Tests were also made on this system under short-circuit conditions. The short circuit comprised a resistance of 47 ohms, or 1.28 on the basis of 435 kv-a. at 4000 volts. This partial short circuit was left on for 0.8 sec. and under these severe conditions, the machines remained in synchronism when carrying an initial load of 330 kw. which is almost twice as much as could be carried by the system with standard regulators under steady conditions.

At a later date a similar system was set up, using machines of the same rating but having a slightly higher value of synchronous impedance, *i. e.*, 1.27 on the basis of 435 kv-a. at 4000 volts. These machines, as in previous tests, were operated at reduced voltage, in this case, 2240 volts, and the power voltage curves under conditions of constant excitation are given in Fig. 17.

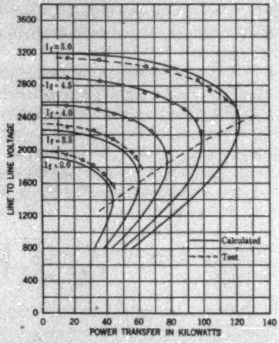

FIG. 17—POWER-VOLTAGE CURVES BY CALCULATION AND TEST

Two TS-6-435-1200-4000/2300-volt synchronous machines connected to the same bus. Excitation on motor and generator held constant at different values

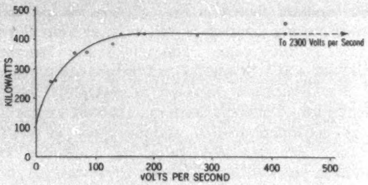

FIG. 18—MAXIMUM POWER AS A FUNCTION OF THE EXCITER VOLTAGE BUILD-UP RATE FOR THE TEST SET-UP OF FIG. 16, USING NEW REGULATOR

The static power limit at 2240 volts is thus 110 kw. When standard automatic voltage regulators were used, as well as hand control, the maximum power under steady load conditions was of the order of 200 kw. The new regulator with the same excitation system increased the maximum power to 415 kw.

Previous tests had indicated that extremely high exciter voltage rates were unnecessary for increasing the maximum power under steady load conditions. Tests were made on this new system to verify this and the results of the tests are shown in Fig. 18. It may be noted that large gains in maximum power are obtained with this new regulator, using exciter voltage rates readily obtainable in standard exciters.

The effects of resistance and inductance inserted in the field circuit were also determined. As previously pointed out, increasing these constants should make it more difficult to obtain large gains in maximum power. These conclusions are justified by the results shown in Fig. 13.

## Appendix

### THEORETICAL CONSIDERATIONS OF VIBRATING CONTACTS

It has been explained that a vibrating contact voltage regulator controls the average exciter voltage by maintaining different ratios of the time that the contacts are closed across a resistance in the exciter field circuit to the time that they are open. Two methods are available for changing from one exciter voltage to another. The contacts may be closed and kept closed until the new average voltage is obtained, vibration being then resumed at a new ratio of time-close to time-open which will maintain the new exciter voltage; or, the ratio of time-closed to time-open may be suddenly changed to its new value, vibration of the contacts being continuously maintained.

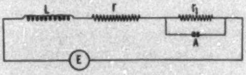

FIG. 19—ELECTRIC CIRCUIT IN WHICH THE AVERAGE CURRENT IS CONTROLLED BY VIBRATING CONTACTS

The transient during the change from one exciter voltage to another is entirely different for the two methods as will be seen from the following analysis.

Consider the circuit shown in Fig. 19 and let

$L$ = inductance of the circuit in henrys.

$r$ = resistance permanently in the circuit.

$r_1$ = resistance periodically short circuited by the contacts, $A$.

$E$ = the constant impressed voltage.

$r_2 = r + r_1$

When the contacts are closed, the differential equation for the circuit is

$$L \frac{d\,i}{d\,t} + r\,i = E \tag{1}$$

The solution of equation (1) is

$$i = \frac{E}{r} - \left(\frac{E}{r} - i_1\right) e^{-\alpha(t - t_1)} \tag{2}$$

where $i_1$ = the current at the instant the contacts close.

$$\alpha = \frac{r}{L}$$

$t_1$ = time at which the contacts close.

When the contacts are open the differential equation is

$$L\frac{di}{dt} + r_2 i = E \qquad (3)$$

and the solution is

$$i = \frac{E}{r_2} - \left(\frac{E}{r_2} - i_2\right)\epsilon^{-\beta(t - t_2)} \qquad (4)$$

where $i_2$ = the current at the instant the contacts open.

$$\beta = \frac{r_2}{L}$$

$t_2$ = the time at which the contacts open.

When the contacts are operating under sustained conditions, the final current of equation (**2**), *i. e.*, at $t = t_2$, must equal the initial current of equation (**4**), and also the final current of equation (**4**), *i. e.*, at $t = t_3$, must equal the initial current of equation (**2**).

Hence $$i_{2s} = \frac{E}{r} - \left(\frac{E}{r} - i_{1s}\right)\epsilon^{-\alpha(t_2 - t_1)} \qquad (5)$$

$$i_{1s} = \frac{E}{r_2} - \left(\frac{E}{r_2} - i_{2s}\right)\epsilon^{-\beta(t_3 - t_2)} \qquad (6)$$

where

$i_{2s}$ = the final current with the contacts closed and the initial current with the contacts open, under sustained conditions.

$i_{1s}$ = the initial current with the contacts closed and the final currents with the contacts open.

Evidently, $t_2 - t_1$ is the time during which the contacts are closed in each vibration and $t_3 - t_2$ is the time that they are open. Letting

$$t_2 - t_1 = t_c = \text{time closed} \qquad (7)$$

$$t_3 - t_2 = t_0 = \text{time open} \qquad (8)$$

equations (**5**) and (**6**) become

$$i_{2s} = \frac{E}{r} - \left(\frac{E}{r} - i_{1s}\right)\epsilon^{-\alpha t_c} \qquad (9)$$

$$i_{1s} = \frac{E}{r_2} - \left(\frac{E}{r_2} - i_{2s}\right)\epsilon^{-\beta t_o} \qquad (10)$$

Solving these simultaneous equations for $i_{2s}$ and $i_{1s}$

$$i_{1s} = E\left\{\frac{\frac{1}{r_2} - \frac{1}{r_2}\epsilon^{-\beta t_o} + \frac{1}{r}\epsilon^{-\beta t_o} - \frac{1}{r}\epsilon^{-(\alpha t_c + \beta t_o)}}{1 - \epsilon^{-(\alpha t_c + \beta t_o)}}\right\} \qquad (11)$$

$$i_{2s} = E\left\{\frac{\frac{1}{r} - \frac{1}{r}\epsilon^{-\alpha t_c} + \frac{1}{r_2}\epsilon^{-\alpha t_c} - \frac{1}{r_2}\epsilon^{-(\alpha t_c + \beta t_o)}}{1 - \epsilon^{-(\alpha t_c + \beta t_o)}}\right\} \qquad (12)$$

Equations (**11**) and (**12**) determine the minimum value, $i_{1s}$, and the maximum value, $i_{2s}$, of the exciter field current under sustained conditions. The variation of current between these limits is given by equations (**2**) and (**4**). The current in the circuit, under sustained conditions, then has the form shown in Fig. 20.

The average current under sustained conditions is obtained as follows:

The area under the current curve during one interval when the contacts are closed is, from equation (**2**),

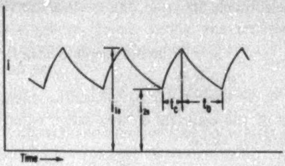

FIG. 20—CURRENT IN THE CIRCUIT OF FIG. 19 AS A FUNCTION OF TIME

$$A_c = \int_{t=t_1}^{t=t_2}\left\{\frac{E}{r} - \left(\frac{E}{r} - i_1\right)\epsilon^{-\alpha(t - t_1)}\right\}dt \qquad (13)$$

$$= \frac{E}{r}t_c - \frac{E}{r\alpha} + \frac{E}{r\alpha}\epsilon^{-\alpha t_c} + \frac{i_1}{\alpha}(1 - \epsilon^{-\alpha t_c}) \qquad (14)$$

The area of the current curve during one interval when the contacts are open is, from equation (**4**),

$$A_0 = \int_{t=t_2}^{t=t_3}\left\{\frac{E}{r_2} - \left(\frac{E}{r_2} - i_2\right)\epsilon^{-\beta(t - t_2)}\right\}dt \qquad (15)$$

$$= \frac{E}{r_2}t_0 - \frac{E}{r_2\beta} + \frac{E}{r_2\beta}\epsilon^{-\beta t_o} + \frac{i_2}{\beta}(1 - \epsilon^{-\beta t_o}) \qquad (16)$$

The average current is then the sum of (**14**) and (**16**) divided by one period of the contacts, $t_0 + t_c$, or

$$i_{ave} = \frac{E\left\{\frac{t_c}{r} + \frac{t_0}{r_2} - \frac{1}{r\alpha} - \frac{1}{r_2\beta} + \frac{1}{r\alpha}\epsilon^{-\alpha t_c} + \frac{1}{r_2\beta}\epsilon^{-\beta t_o}\right\} + \frac{i_1}{\alpha}(1 - \epsilon^{-\alpha t_c}) + \frac{i_2}{\beta}(1 - \epsilon^{-\beta t_o})}{t_0 + t_c} \qquad (17)$$

When equations (**11**) and (**12**) are substituted in (**17**) the average sustained current is,

$$i_{ave} = E\left\{\frac{\frac{t_c}{r} + \frac{t_0}{r_2}}{t_0 + t_c} - \frac{L}{t_0 + t_c}\left(\frac{r_2 - r}{r_2 r}\right)^2\right.$$

$$\left.\frac{(1-\epsilon^{-\beta t_o})\,(1-\epsilon^{-\alpha t_c})}{(1-\epsilon^{-(\alpha t_c+\beta t_o)})}\right\} \qquad (18)$$

Since $\frac{1}{r}$ is the conductance of the circuit when the contacts are closed, and $\frac{1}{r_2}$ is the conductance when the contacts are open, the average current, when $L = 0$, is

$$i_{ave} = E \text{ (average conductance)} \qquad (19)$$
$$L = 0$$

When L is very large or when the frequency of vibration of the contacts is very large, equation (**18**) approaches the value

$$i_{ave} = \frac{E}{\dfrac{r\,t_c + r_2\,t_0}{t_0 + t_c}} \qquad (20)$$

$L = \infty$ or $t_0 + t_c = 0$

or the average current, for these conditions, is determined by the average resistance. In most practical cases, the combined effects of inductance and contact frequency will be sufficiently great to make equation (**20**) a good working approximation.

The manner in which the average sustained current changes from one average value to another is of importance in the problem of maximum power. When the change is initiated by suddenly changing the ratio of the time that the contacts are closed to the time that they are open, the new sustained value of current is not attained in one vibration of the contacts but only after a relatively long transient. For one closing of the contacts at the time $t_1$, the initial current is $i_1$. The current increases to $i_2$ determined by equation (**2**), and $i_2$ is the initial current when the contacts open. After they open, the current decreases to a new value

$$i_3 = \frac{E}{r_2} - \left(\frac{E}{r_2} - i_2\right)\epsilon^{-\beta t_0} \qquad (21)$$

determined by equation (**4**), and $i_3$ is the initial current when the contacts again close. Under sustained conditions, $i_3 = i_1$, but when the ratio of $t_c$ to $t_0$ is suddenly changed, $i_3 \neq i_1$ until the new sustained values are reached.

During the transient period, the difference between $i_1$, for a given closing of the contacts, and its final sustained value, $i_s$, given by equation (**11**), is

$$i_{1s} - i_1 =$$
$$E\left\{\frac{\dfrac{1}{r_2} - \dfrac{1}{r_2}\epsilon^{-\beta t_o} + \dfrac{1}{r}\epsilon^{-\beta t_o} - \dfrac{1}{r}\epsilon^{-(\alpha t_c+\beta t_o)}}{(1-\epsilon^{-(\alpha t_c+\beta t_o)})}\right\}$$
$$- i_1 \qquad (22)$$

The difference between the new sustained value, $i_{1s}$, and $i_3$, one cycle of vibration later, is

$$i_{1s} - i_3 = E\,\epsilon^{-(\alpha t_c+\beta t_o)}$$
$$\left\{\frac{\dfrac{1}{r_2} - \dfrac{1}{r_2}\epsilon^{-\beta t_o} + \dfrac{1}{r}\epsilon^{-\beta t_o} - \dfrac{1}{r}\epsilon^{-(\alpha t_c+\beta t_o)}}{(1-\epsilon^{-(\alpha t_c+\beta t_o)})}\right\}$$
$$- i_1\,\epsilon^{-(\alpha t_c+\beta t_o)} \qquad (23)$$

The ratio obtained by dividing (**23**) by (**22**) is

$$d = \epsilon^{-(\alpha t_c+\beta t_o)} \qquad (24)$$

This is the value of the decrement of the minimum current values per cycle of vibration of the contacts. Since this ratio is constant, the envelope of the minimum current values is exponential in form, and the current, for any instant at which the contacts close, is

$$i_1 = i_{1s} - (i_{1s} - i_{10})\,\epsilon^{-\left(\frac{\alpha t_c+\beta t_0}{t_c+t_0}\right)t} \qquad (25)$$

The decrement factor of (**25**) is

$$\sigma = \frac{\alpha\,t_c + \beta\,t_0}{t_c + t_0} = \frac{r\,t_c + r_2\,t_0}{L\,(t_c + t_0)} = \frac{\text{average resistance}}{L} \qquad (26)$$

It is interesting to note that although the sustained average current is determined by the average conductance when $L$ is zero, [equation (**19**)], by the average resistance when $L = \infty$, [equation (**20**)] and by some intermediate value when the inductance is finite, nevertheless, the time constant during a transition period is always a function of average resistance.

It can be shown that the maximum current peaks and average current also vary according to the same exponential law. Hence, when the ratio of time-closed to time-open is suddenly changed, the average current changes from its initial sustained value to its final sustained value according to equation (**27**).

$$i_{ave} = i_s - (i_s - i_0)\,\epsilon^{-\frac{\text{average resistance}}{L}t} \qquad (27)$$

where $i_s$ is the final and $i_0$ the initial sustained average current. During this transient, the current will appear as shown in Fig. 10.

Inspection of Fig. 10 shows how much slower the exciter field current builds up when the contacts open and close during the change in field current than when they close and remain closed until the exciter field current has reached its new value. With the slower scheme, the effective rate of change of exciter field current is given by the slope of the exponential curve through the current peaks, *i. e.*, by the slope of line $A$; whereas, if the contacts close and stay closed until the new average value of exciter field current is reached, the effective rate of change of field current is given by the slope of line $B$. The new regulator functions in this way and the marked results obtained with it are largely due to this characteristic.

The superiority of this principle may be brought out by the following example.

Let Fig. (21) represent the saturation curve and field characteristic of an exciter which is controlled by a regulator whose contacts close and open during the change in field current. Assume that the contacts are vibrating 5-times per sec. and that the initial time-closed and time-open intervals are

$$t_c = 0.04 \text{ sec.}$$
$$t_0 = 0.16 \text{ sec.}$$

Then the average field current, determined by equation (**21**), is 3.67 amperes, the corresponding exciter voltage, from Fig. 21 is 110 volts, and the ratio of time-closed to time-open is $\frac{t_c}{t_0} = 0.25$.

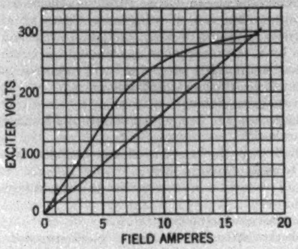

Fig. 21—Saturation Curve and Field Characteristic of the Exciter Used in the Numerical Example

Voltage impressed on exciter field, 500 volts. Resistance of field winding, 16.67 ohms. External resistance, 166.67 ohms

When the ratio of time-closed to time-open is suddenly increased to some new value, the initial rate of change of average exciter field current, can be determined by means of equations (**18**) and (**27**). The rate of change of average exciter voltage may then be obtained from Fig. 21. The curve in Fig. 22 shows the initial rate of change of average exciter voltage in volts per second when the ratio of time-closed to time-open is changed.

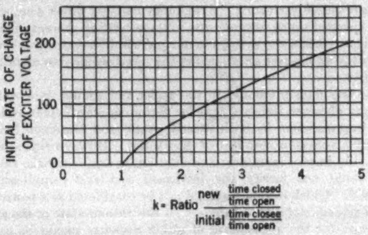

Fig. 22—Rate of Change of Average Exciter Voltage as a Function of Changes of the Ratio of Time-Closed to Time-Open of the Vibrating Contacts

It will be noticed that, as the change in this ratio becomes smaller, the effective rate of change of exciter voltage also becomes smaller, approaching zero as a limit. Hence at incipient breakdown, where the changes of this ratio are small, a regulator which closes and opens its contacts during the change in field current is very ineffective and the synchronous machines will acquire some momentum on their way out of synchronism before the regulator becomes very effective. It is thus apparent that the machines are allowed to get under way, out of synchronism which is usually fatal as far as operation under conditions of dynamic stability is concerned.

If, with *the same exciter*, a regulator is used which keeps its contacts closed during the transient, the initial rate of change of average exciter voltage becomes *438 volts per sec.*

Therefore, a regulator which continues to vibrate its contacts during a change of exciter field current causes the apparent or effective speed of exciter build-up to be markedly less than its inherent speed.

In many cases, the necessity for abnormal exciter voltage rates may be overcome by using the new regulator which takes advantage of the inherent exciter speed at all times.

## Discussion

**C. A. Powel:** The problem of quick-response excitation in its relation to stability is one of great importance, and one in which I have been much interested. In fact, I believe my paper prepared for the "High Voltage Conference" at Paris last year, and later published in the *Electric Journal* of April 1927, was the first one devoted exclusively to quick-response excitation. Mr. Doherty's paper is interesting and valuable in itself, and also because it disposes of a controversy over a major question in the general problem of stability. He refers to a heretofore unexploited zone of artificial stability, and it may be interesting to review the work previously done in this zone.

At the A. I. E. E. Mid-Winter Convention in 1924, E. B. Shand[1] suggested that operation in the zone of artificial stability might be possible if we could change the excitation within the synchronous machine quickly enough. The idea was further developed in the course of our work on high voltage transmission, and at the Mid-Winter Convention in 1925, Messrs. Fortescue and Wagner[2] were able to amplify considerably Mr. Shand's ideas. In September 1925, at the Seattle Convention, Mr. Fortescue[3] definitely proposed an increased speed of excitation obtained by regulator control as a means of increasing the stability of a transmission system, and Mr. Doherty and his colleagues specifically disagreed with him, maintaining the position that quick response, if it was to be obtained by means of a voltage regulator, would not make it possible to carry a constant load significantly greater than with hand control. Mr. Doherty expressed himself as being of the opinion that improvements by compensation rather than by regulation were a more hopeful field for future development. Such improvements have been suggested in the past and involve either a series exciter or compounding by means of rectifiers or converters.

At the Mid-Winter Convention in 1926, Messrs. Evans and Wagner[4] presented a paper which summarized the exploitation, by them and their colleagues, of the range of operation of synchronous machines beyond the static limit as set by constant excitation, both with steady loads and under transient conditions. At the time, Mr. Doherty and Mr. Nickle again asserted that the only function of the regulator was to increase automatically the excitation as the load is applied, the actual load limit being the same as for hand control; whereas Messrs. Evans and Wagner described in their closing discussion tests made at Pittsburgh in 1925. The tests were made with an artificial line having 100 per cent reactance based on the normal rating of the machines, and using a standard Westinghouse vibrating regulator. With this combination, a substantial increase over the static limit was transmitted over this miniature system.

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[1] *The Limitations of Output of a Power System Involving Long Transmission Lines.* A. I. E. E., Trans., 1924, Vol. XLIII, p. 59.

[2] A. I. E. E. Trans., 1925, Vol. XLIV, pp. 98-101.

[3] *Transmission Stability,* C. L. Fortescue, A. I. E. E. Trans., 1925, Vol. XLIV, p. 984.

[4] *Studies of Transmission Stability,* A. I. E. E. Trans., 1926, Vol. XLV, p. 51.

In one of the subsequent tests described by Mr. Doherty in the paper under discussion, he obtained four times the static limit of the system with a set-up consisting of a generator and motor on a common bus with a common exciter and regulator. Now with ideal excitation and neglecting losses and saturation, the theoretical power limit of such a set-up would be infinity; whereas with a set-up consisting of a generator and motor connected by a transmission line, the stability limit is the power limit of the line itself, which is finite. The tests which Mr. Doherty reports, using an artificial line and independent control of the sending and receiving machines, give results higher than the tests made in Pittsburgh in 1925, but the latter were made with a view of establishing the facts, and not of finding the ultimate limit.

The tests are interesting, but I question if they are of the practical value that the paper implies. The true power limit of a system under present-day conditions is defined by its stability under transient conditions. Those who are operating transmission systems know that when the two ends of a system pull apart, they do so at times of a disturbance, and not as a result of slowly added load. Now for transient conditions, any a-c. control regulator, such as the Westinghouse regulator, that closes its contacts promptly and keeps them closed until the a-c. voltage is back to approximately normal, is suitable. After the regulator has closed its contacts, the recovery of the a-c. voltage is a function of the response of the exciter and generator.

Moreover, operating a system with steady loads in the zone of artificial stability as suggested, requires that the rotors of the generating units be worked at very high values of excitation, and it may be more desirable, either to increase the static limit itself by reducing the reactance of the generators, or to supply the excitation at more appropriate locations along the transmission system, as advocated in the Baum system of transmission using intermediate synchronous condensers.

**R. D. Evans:** Concerning the relation of excitation to stability, there are, as Mr. Doherty points out, two distinct problems involved:

1. The use of excitation systems to increase transient limits of power systems.

2. The use of excitation systems to increase the steady load limits of power systems.

The question naturally arises as to the relative importance of these two uses of excitation systems. This depends, of course, on whether the static limit or the transient limit is the criterion for establishing the permissible loading of the power system. The oscillographic records of operating experiences on the Southern California Edison Company system, given in the paper by Messrs. Wood, Hunt, and Griscom, presented at the Pacific Coast Convention of the A. I. E. E. last September, have established that the transient limit is the more important. Ignoring those cases involving low excitation due to line-charging condition, very small ties, insufficient frequency-changer ties, and so on, there is only one case on record where the static limit of a large power transmission system has been exceeded and that case occurred under very abnormal operating conditions. Thus one must conclude that the use of excitation systems to increase transient stability limits is the immediate problem while the increase in static limit is of less pressing nature.

Now I wish to stress the fact that considerations of transient limits have been controlling in the acceptance and adoption of quick-response excitation. Quick response was not made possible by the introduction of any new regulator, as its advantages can be obtained with existing forms of a-c. regulators. The recognition of the interest in this method of increasing the transient limit is evidenced by the fact that while the first order for such apparatus was placed during 1926, the scheme has been so widely adopted that the Westinghouse Company alone has received orders for quick-response excitation systems for about one million kv-a. of synchronous machines.

As to the requirements of excitation systems for increasing the transient limits, the most important are:

For the voltage regulator:

1. It shall close the contacts promptly upon a demand for increased excitation.

2. It shall keep the contacts closed until the a-c. voltage is restored to an appropriate value.

3. It shall possess the necessary anti-hunting features.

For the exciter:

It shall possess quick response.

Mr. Doherty attempts to define quick-response systems in terms of exciter characteristics, that is, in terms of volts per second. Such a definition, however, is not fundamental to quick response to increase stability limits of power systems. Any excitation system (which, of course, includes the regulator as well as the exciter) which is sufficiently quick to make an important change in the excitation voltage before the synchronous machine has had time to swing to a dangerous angle, beyond which recovery would be doubtful, is quick response. Or, considered from the standpoint of the fluxes in the synchronous machine, any excitation system that is quick enough to prevent a significant reduction in flux interlinkages due to demagnetizing armature current, as from a short circuit or other system disturbance, is quick response.

As a result of stability studies it has been established that a system will reach a critical point in its oscillation in something of the order of three-quarters of a second after the initiation of a disturbance, so that any corrective action, to be effective, must be made in less time than that. This requires a quicker exciter response than was used prior to the introduction, by us, of quick-response excitation. Previously exciters which were slow were speeded up to improve the voltage settling characteristics; that is, to restore the voltage to normal within a reasonable time; but not to any degree approaching the speed required to maintain stability.

The test data presented in the paper and similar data which we have obtained indicate that for certain applications considerable improvement in both steady static and transient limits result by increasing response of the exciter. However, in certain cases, the improvements in stability limits are extremely small and would not justify the increased cost and complication incurred. Quick response should not be considered as a panacea for all system stability troubles. In the present state of the art, each case for the application of quick response should be considered on its own merits.

**J. H. Ashbaugh:** The description of the exciter rheostatic regulator might give one the impression that this regulator is, if sensitive, always in a state of vibration. This is not true below the region of the static-state limit and I assume that Messrs. Nickle and Carothers did not intend to give this impression. The vibrating regulator will not maintain voltage much closer than 0.5 per cent due to imperfection of contacts. This imperfection of contacts is not present in the exciter rheostatic regulator so that it is just as sensitive as the vibrating regulator.

When transient stability is to be considered the exciter rheostatic regulator short circuits the exciter field rheostat the same as a vibrating regulator, which is in my opinion all any regulator can do for the condition.

Another feature which I should like to emphasize is the anti-hunting device. The hunting associated with the type *D* regulator is probably due to improper adjustment rather than the particular form of anti-hunting device as evidenced by tests. Messrs. Nickle and Carothers state that "The proper time-phase relations are obtained largely by the mechanical design of the regulator and the use of anti-hunting devices as have been used in the past." I am somewhat inclined to this point of view and believe that the particular anti-hunting device used in this new regulator is but one of several that would be found satisfactory.

From tests which I have conducted I do not believe that the results with the type *D* regulator as outlined in Mr. Doherty's paper are representative of this regulator. It has been my experience that greater gains than shown were obtained with an increase in volts per second of the exciter. There are several features of importance with regard to adjustment of this regulator. These have an important bearing when steady-state limit as well as transients are considered.

**C. A. Adams:** The substance of the discussion thus far is to the effect that other regulators are just as satisfactory for the control of transient instability and that there is no need of control for continuous instability, owing to the fact that synchronous machines are not continuously operated in the unstable zone.

Concerning the operation of other regulators under conditions of transient instability, I cannot speak with authority, but I do know that this particular regulator does operate and is operating to protect against transient instability.

I cannot agree with the opinion that nothing is to be gained by a regulator which will enable synchronous machines to operate continuously in or near to the unstable zone and for the following reasons:

In the early days when alternators were practically all of the low-speed multipolar type, very close inherent regulation was specified; so close, in fact, that the armature short-circuit ratio was often as high as from 3-to-5, or even 6. Moreover, with the type of machine then prevalent, this high short-circuit ratio did not constitute any considerable handicap to the designer. However, the whole situation was changed with the advent of the high-speed turbo alternator, where the limit of capacity is determined by the maximum allowable peripheral current density on the rotor. This point will be more readily appreciated from the vector diagram, Fig. 1 herewith. This is a simplified magnetomotive force diagram where *F* represents the field magnetomotive force, *A* the equivalent armature magnetomotive force proportional to the armature current, and *R* the resultant or reluctance magnetomotive force sufficient to produce a flux, the cutting of which by the armature conductors will generate the terminal voltage, ohmic drop in the armature being neglected.

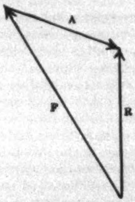

Fig. 1

The short-circuit ratio is approximately equal to $R/A$. For a given machine *F* is a measure of the peripheral current density (ampere-conductors per inch of periphery) on the rotor, and *A* of the peripheral current density on the stator.

Owing to tooth contraction on the rotor and to the requirements of mechanical strength of the teeth, the space available for copper per inch of periphery is absolutely limited, and hence the peripheral current density of the rotor. This is not the case on the stator, as there is no practical limit to the slot depth.

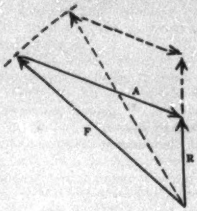

Fig. 2

Thus the real limit to the peripheral current density on the stator is the peripheral current density on the rotor and the maximum allowable ratio between the two; that is, between *A* and *F* in the diagram. The larger this ratio with the limiting value of *F*, the higher will be the possible rating and capacity of a machine of given air-gap dimensions; or, to put it in another way, for a smaller armature short-circuit ratio, which means a lesser inherent stability, the armature peripheral current density and *A* in the diagram can be larger for the same limiting value of *F*. This is shown in Fig. 2, herewith, in which Fig. 1 is reproduced in dotted lines and the diagram for the new machine of higher rating is shown in solid lines. *F* is the same for both of these machines. *A* is considerably larger for the new machine with the lower short-circuit ratio and the lesser inherent stability. *R* has been reduced, which simply means a shorter air-gap.

It is thus possible to increase the output of turbo generators with given length and rotor diameter, by shortening the air-gap and increasing the peripheral current density and copper on the armature.

The only reason why this has not been done before is because the resulting reduction in inherent stability was looked upon as dangerous. If, however, reliable regulators can be provided which will eliminate the danger from the reduction of inherent stability, I can see no reason why a considerable increase in capacity cannot be obtained at very small cost.

Therefore, a regulator which will accomplish this result certainly constitutes a real advance in the art of power generation and transmission.

**R. H. Park:** One of the most interesting results shown in the papers is the large difference between the operation of the new regulator, and the operation of the regulator without d-c. coil. Thus the data show that under steady load conditions the maximum power which could be carried, under the test conditions, was as follows:

| | |
|---|---|
| New regulator | 415 kw. |
| Regulator without d-c. coil | 225 kw. |

Subsequent tests with different adjustments indicated improved operation of the latter regulator. The results of these tests were as follows:

(A) Dynamic limit, steady load, two machines tied directly together.

| | Maximum power transient possible with stability |
|---|---|
| New regulator* | 415 kw. |
| Regulator without d-c. coil (best adjustment) | 259 kw. |
| Hand control (fixed excitation) | 110 kw. |

(The exciter speed used in connection with tests was approximately 250 volts per sec. It was found that increasing the speed of excitation did not improve the operation.)

(B) Same as (A) except shunt load of 124 kv-a. at 0.124 power factor.

| | Maximum motor load possible with stability |
|---|---|
| New regulator | 461 kw. |
| Regulator without d-c. coil (best adjustment) | 317 kw. |
| Hand control (fixed excitation) | 173 kw. |

(C) Same as (A) but machine separated by model 250-mile line.

| | Maximum motor power possible with stability |
|---|---|
| New regulator | 105 kw. |
| Regulator without d-c. coil | 98 kw. |
| Hand control (fixed excitation) | 67 kw. |

(D) Same as (C) but shunt load of 62-kv-a. at 0.12 power factor at motor end.

| | Maximum motor power possible with stability |
|---|---|
| New regulator | 88 kw. |
| Regulator without d-c. coil | 82 kw. |
| Hand control (fixed excitation) | 57½ kw. |

(E) Same as (A) but machines separated by a 500-mile line:

| | Maximum power possible with stability |
|---|---|
| New regulator | 59 kw. |
| Regulator without d-c. coil | 59 kw. |
| Hand control (fixed excitation) | 43 kw. |

(F) Different machines separated by a reactance equal to 52 per cent of machine synchronous reactance, dynamic limit steady load.

| | Maximum power possible with stability |
|---|---|
| New regulator | 63 kw. |
| New regulator with two torque motors instead of one torque motor and one a-c. coil | 63 kw. |
| Regulator without d-c. coil | 51 kw. |
| Hand control (fixed excitation) | 38 kw. |

The result of these tests is to confirm definitely the fact of an essential difference in operation between the two regulators; that is, to confirm one of the general theses of the papers that the new regulator in general possesses special characteristics particularly fitting it for controlling the operation of synchronous machines under conditions where dynamic stability is at a premium. This difference, however, as well as the gain which the regulator makes possible over hand control, diminishes as the length of line increases. The variation of dynamic limit of the two regulators, with length of intermediate line, is shown in Fig. 3 herewith. It will be seen from the figure that for lines of ordinary length the relative advantage of the new regulator is considerable.

After it is clear that there is a gain, it may be enquired whether these gains obtain in practise, or whether they apply to shop tests only. This point has not been completely explored yet. Experience has shown that the differential between the operation of the new regulator and the regulator without the d-c. coil decreases somewhat as the size of the machines tested increases. Therefore one difference which may be anticipated is that in the case of large machines this differential will be reduced.

Another difference is that in the tests made saturation was not present. Saturation, because it of itself tends to improve stability, reduces to some extent the gain which the regulator can accomplish.

Next it may be enquired where these gains in dynamic stability will be realizable. Of course, in most cases maximum power is not, as yet, felt as a limitation to normal operation. On the other hand, there are cases where the limitation of maximum power is encountered under normal conditions. These are in connection with power transmission over long lines, and in connection with power transmission over short lines where the power per circuit is very high. Of course, it is in just these cases that stability is of the greatest importance.

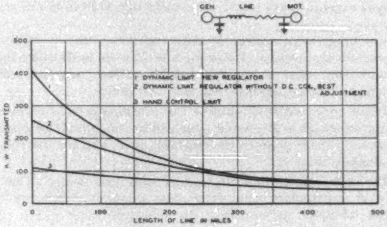

Fig. 3

Another instance is that of emergency conditions of operation. Thus, suppose a short circuit occurs and a line is dropped. In such a case it may be of great advantage to transmit a maximum of power over a weak tie line. In this case ability to operate in the zone of artificial stability should be of value.

A further consideration of very great importance is, how the regulator acts, during and after short circuits and sudden load changes. Thus, it might be supposed that the ability of the regulator to operate above the steady-state limit would disappear when short circuits and other disturbances are encountered. However, tests show that this is not the case. In general, the regulator is found to have two effects under transient conditions of operation, one an increase in the amount of power that can be carried with hand regulation, another a reduction in the tendency of machines to hunt. The amount of gain depends upon the severity of the short circuit or other disturbance. If the disturbance is slight, the gain is almost as great as that obtaining under steady conditions of operation. As the other extreme, a test in which 140 per cent resistance load is suddenly thrown onto two machines connected directly together, for a period of 0.6 sec., shows that the 230 per cent of the static limit can be carried with stability.

A test result is also available in an even more severe case. This case corresponds to a very severe short circuit on one of two parallel 250-mile lines. With the short circuit cleared at both ends in 0.6 sec., it was found that, with the new regulator, 108 per cent of the static limit of one line could be carried with stability.

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*Same as described in paper except right-hand a-c. coil replaced by a torque motor.

Thus, the new regulator effects an improvement in stability, both under steady and transient conditions. As mentioned above, the gains under transient conditions are greater when the severity of the short circuit is less; if the short circuit is out in the middle of the line, it may be only half as severe, and consequently greater gains in stability due to the regulator are possible.

One other point of interest which may well be mentioned here is the fact that in general a somewhat different adjustment is required for best operation under transient conditions from that required under dynamic conditions. As shown by Nickle and Carothers in their paper, in the event of a short circuit or other disturbance involving a drop in machine terminal voltage the regulator acts to increase the exciter voltage in two steps, first by a sudden increase, in one vibration of the contacts, to an initial value; second, a process of continuous vibration according to which the terminal voltage is brought back to normal with a speed dependent on the degree of damping in the dashpot attached to the right hand lever. This process is illustrated in Fig. 4 herewith.

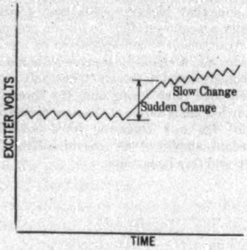

Fig. 4

The magnitude of the sudden change is freely adjustable through variation of the relative strengths of the d-c. and the a-c. elements on the left-hand lever, or, in the case of the type B regulator, by variation of the d-c. element and the stiffness of the spring in the spring dashpot.

From an analytical point of view, weakening the strength of the d-c. element relative to that of the a-c. element or the degree of elastance of the spring dashpot, corresponds to an increase in the negative resistance which the regulator inserts in the machine field. For best results under transient conditions the data at present available indicate that a low ratio of strengths of the d-c. and a-c. elements is desirable, thus corresponding to more than enough negative resistance in the machine field to compensate for its inherent positive resistance. (In general, the attainment of best all-around operation requires an adjustment involving some reduction in dynamic stability.) The exact adjustment to be employed in any particular case is variable depending on the severity and probable duration of the disturbances anticipated. The flexibility of the regulator by which it can be readily adjusted to meet any operating condition, is one of its most desirable characteristics.

**C. A. Nickle:** The discussions just presented seem to indicate that there is no serious disagreement with the main points brought out in this paper. With regard to the rheostatic type of regulator, its ability to regulate voltage under conditions of dynamic stability has been determined by test and we find that it does not seem suitable for this particular condition of operation. However, it is unquestionably satisfactory for operation below the static power limit and can satisfactorily take care of short circuits under this condition. It has been stated in the paper that this type of regulator has certain advantages not possessed by other types.

Mr. Powel has expressed the opinion that for transient conditions the only requirement of a regulator is that it close its contacts and keep them closed until the voltage is restored to approximately normal value. However, we do not believe that this is the only requirement for achieving the greatest stability under transient conditions. Sudden shocks, such as are imposed on a system by short circuits, necessarily result in system oscillations, and a regulator must be able to damp out such oscillations effectively. Otherwise, the system may break from synchronism, even after the exciting disturbance is over. The fact that a regulator closes its contacts promptly and keeps them closed until the voltage is approximately restored to normal, does not necessarily imply that the regulator has the proper antihunting characteristics.

**R. E. Doherty:** The most significant point about the discussion is that there appear to be no essential points of disagreement with what the authors consider to be the main contribution of the papers.

The foremost fact is that regulating means for increasing the maximum power of synchronous machines under conditions of dynamic stability have been much improved. Very substantial increases in maximum power above the steady-state limit, obtained by the use of the improved regulator, are given in the present papers. I do not find that anyone has questioned this fact.

To obtain such increases is an objective which has been actively sought during the last 4 or 5 years by engineers interested in power transmission. Credit is due to C. L. Fortescue for having apparently foreseen more clearly than any one else the possibility of attaining the objective by an improved regulator, and for predicting its development. Referring to tests which had demonstrated to him the *possibility* of operating in synchronism above the steady-state power limit by the use of an automatic voltage regulator (which I understand to be the a-c. coil type referred to by his associates in the present discussion), he made the following prediction at the Mid-Winter Convention in 1926:

"Now I am bringing out this point not to emphasize the point of difference, but because this artificial stability has an element of hope in it. If you can do it with a regulator today, you may be able to get a regulator that will do it still better tomorrow. You will surely be able to get more power over a given line tomorrow. Maybe the automatic regulator of special design will be the answer; maybe the inherent regulator scheme will be the answer. We don't know now, but one of these days we will know."

Such an automatic regulator of special design is now an accomplished fact, and the possible gains in maximum power by its use are promising in connection with the general development of power transmission.

Another noteworthy point on which there is practical agreement is the importance of operating through system disturbances—usually referred to under the heading of transient stability. It is agreed that this must be accomplished to the greatest practicable extent, whether the system is normally operated above the static limit or not.

Our tests show that the new regulator is efficacious in increasing the transient, as well as the dynamic, stability. In other words, it increases the power which can be carried through a system disturbance, as well as that which can be carried under steady load conditions. This is illustrated by the data which Mr. Park has given.

Thus, with reference to all of the foregoing, there appears to be no question raised in the discussion as to the results accomplished by the regulator. Nor do I find any adverse comment regarding the general theory as to how those results are accomplished—*i. e.*, by the introduction of the effect of negative resistance[5] in the field circuit by the use of the regulator. Thus as to the results and the theory which explains them, there seems to be no disagreement. And the authors regard these as the main contributions in the papers.

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[5] It is recognized that regulators using other principles of operation can also introduce negative resistance and thus increase stability limits.

There are, however, some minor details which require explanation. Thus we are criticized, and perhaps justly, for not mentioning a test reported to have been made in 1925 in which the possibility of passing the steady-state limit was noted. However, the pertinent data regarding this test are not fully given in the literature, to our knowledge, and we know of no test since then which is comparable with those reported in the present papers. As to that one test, the conclusion drawn is freely acknowledged, namely, that it is possible to pass the steady-state limit by the use of the a-c. coil type of regulator.

As to other questions, Mr. Powel refers to the tests of Fig. 3 of my paper in which about four times the static power limit was obtained, with the statement that the ideal limit is infinity. This is merely a question as to what is taken as a standard of idealness. If the limit of the intermediate line is the standard Mr. Powel's figure is correct. However, we believe that a better standard is the degree to which the regulator compensates for armature reaction. On this basis the limiting power for comparison is that corresponding to transient reactance, and that limit is reasonably approached.

The advantage of the test with no intermediate line is that it shows the extent to which the regulator increases the capacity of the machines themselves, which is the object of the regulator. It is of course not intended that the regulator should neutralize the constants of the line. Calculations show that in practise the regulator compensates for about 95 per cent of armature reaction (*i. e.*, 95 per cent of $x_d - x_d'$).

At present it does not seem possible to overcompensate for armature reaction. Looking to the future, however, the perfection of the mercury arc rectifier and allied devices gives promise of affording improved regulating means embodying most of what appear to be the ideal regulating characteristics. With such a regulator, which would not involve vibrating contacts, it may be possible to overcompensate the armature reaction without inducing hunting.

As to "quick response," Mr. Evans questions my definition and proposes a new one. I hold no brief for the one I suggested. In the interest of accurate statement, I merely said what I meant by quick response. Now we have what Mr. Evans means by it. Any definition is all right which is generally accepted, or if not accepted, then accurately understood.

At the present writing sufficient data are not available to permit an exact statement of the best method of fulfilling excitation requirements in any given case. It would appear, however, that in many cases a moderate speed of response, say of the order of 200 volts per second on 250-volt fields, and half that much on 125-volt fields, would be sufficient. At the same time there are cases where somewhat higher speeds are desirable. Where conditions justify a maximum effort to obtain transient stability, the desirable arrangement would appear to be a combination of the new regulator and a stand-by super-excitation, the function of the latter being merely to "shoot" the excitation voltage to an appropriately high value during only the short interval of ½ second or so, the balancing action of the new regulator then being resumed. Since the new regulator itself affords first-order gains in transient stability, the combination should afford additional gains and thus be justified.

# Report of the Board of Directors

## FOR THE FISCAL YEAR ENDING APRIL 30, 1928

The Board of Directors of the American Institute of Electrical Engineers presents herewith to the membership its Forty-fourth Annual Report, for the fiscal year ending April 30, 1928. A general balance sheet showing the condition of the Institute's finances on April 30, 1928, together with other detailed financial statements, is included herein. The following is a brief summary of the principal activities of the Institute during the year, more detailed information having been published from month to month in the Institute JOURNAL.

**Directors' Meetings.**—The Board of Directors held seven meetings during the year, six in New York and one at Detroit, Michigan. The Executive Committee acted upon various matters during intervals between board meetings.

Information regarding the more important activities of the Institute which have been under consideration by the Board of Directors, the committees and the various officers, is published each month in the section of the JOURNAL devoted to "Institute and Related Activities."

**President's Visits.**—President Gherardi has attended three national and three regional conventions of the Institute during the past year and in addition has visited many of the Sections.

The following is a list of places visited: Detroit, Mich. (Summer Convention); Del Monte, Calif. (Pacific Coast Convention); New York, N. Y. (Winter Convention); Chicago, Ill. (Regional); St. Louis, Mo. (Regional); Baltimore, Md. (Regional); Regina, Can. (Saskatchewan Section); Vancouver, B. C.; Seattle, Wash.; Portland, Ore.; San Francisco, Calif.; Los Angeles, Calif.; Salt Lake City, Utah; Denver, Colo.; St. Louis, Mo.; Pittsburgh, Pa.; Ithaca, N. Y.; the president is scheduled to visit other Sections during May and the Annual Summer Convention in June.

**Meetings.**—Three national conventions of the Institute were held during the year, namely, the Summer, Pacific Coast, and Winter. The Annual Business Meeting was held in May. Regional meetings under the auspices of the Geographical Districts were held in Pittsfield, Mass., District No. 1; Chicago, Ill., District No. 5; St. Louis, Mo., District No. 7; Baltimore, Md., District No. 2.

**Annual Meeting.**—The Annual Business Meeting was held at Institute headquarters, New York, on May 20, 1927. The Annual Report of the Board of Directors for the fiscal year ending April 30, 1927, was presented. The Tellers Committee made its report upon the election of officers for the administrative year beginning August 1, 1927.

**Summer Convention.**—The Forty-third Annual Summer Convention was held at Detroit, Michigan, June 20-24, 1927. Six technical sessions were held, at which twenty-three papers and a symposium on television were presented. In addition, three other sessions were held, one being devoted to a lecture on "The Physical Nature of the Electric Arc" by Dr. K. T. Compton, and two to the presentation of fifteen technical committee reports. The Annual Conference of the Sections Committee was held on Monday, June 20; forty Sections were represented. The entertainment features included golf and tennis tournaments, a dinner, a boat trip, sightseeing, and special features. Numerous inspection trips were also made. About 1200 members and guests attended.

**Pacific Coast Convention.**—The Sixteenth Pacific Coast Convention was held at Del Monte, California, September 13-16, 1927. Four technical sessions and a general meeting were held, at which fifteen papers were presented and two addresses given. Attendance about 250.

**Winter Convention.**—The Sixteenth Winter Convention was held in New York, N. Y., February 13-17, 1928. At nine sessions twenty-nine technical papers were presented; a symposium on interconnection and its effect on power development (which included four papers and much discussion), a lecture, and a joint meeting with the Institution of Electrical Engineers by means of transatlantic telephony, were held. At another session the presentations of the John Fritz and Edison Medals took place. Numerous inspection trips, a smoker, and a dinner-dance were held. Attendance about 2000.

**Regional Meetings.**—Four regional meetings were held during the year:—the first in District No. 1 at Pittsfield, Mass., May 25-28, 1927, six technical sessions comprising forty papers were held, including one session devoted to the presentation of nine Student papers, attendance 550; second at Chicago, Ill., in District No. 5, November 28-30, four technical sessions were held, at which thirteen papers were presented, attendance 900; third at St. Louis, Mo., in District No. 7, March 7-9, 1928, four technical sessions were held at which fourteen papers were presented, attendance 500; fourth at Baltimore, Md., in District No. 2, April 17-20, four technical sessions were held, at which twelve papers were presented, attendance 400. Inspection trips and social events were a part of each of these meetings.

The importance of the regional type of meeting has been further demonstrated during the year. The total attendance at the four regional meetings was 2350 and the total attendance at the three national conventions was 2930. This large attendance and the increased interest in the Institute throughout the country, which has developed as a result of the meetings, indicate that they are a very important part of the Institute's activities.

The regional committees which have had charge of these meetings are to be highly commended for their work. The success of the meetings has been due to their ability to plan, organize, and conduct the meetings.

**Sections.**—During the past year a large majority of the Sections has been very active. A considerable number of meetings has been devoted to general or moderately technical subjects of unusual interest with excellent results, and interest in purely technical meetings has been well-maintained. The success of the four regional meetings held during the year (see listing under Regional Meetings) furnishes additional evidence of Section activity.

The Columbus and Worcester Sections became members of the newly organized Affiliated Technical Societies of Columbus and Affiliated Engineering Societies of Worcester, respectively. About one-half of the Sections are now definitely affiliated in some manner with other local organizations.

At the 1927 Sections Committee Conference, progress was made in the development of means of bringing about closer relations between engineers and the general public, and an increased interest in the subject has become apparent. It was recommended that a combined report on Section and Branch activities be prepared annually beginning with the fiscal year ending April 30, 1928, and a general plan for the report has been approved by the Board of Directors.

Many Sections have continued to carry on very effective co-operation with neighboring Student Branches by sponsoring Student Conventions, having student programs at regular Section meetings, or holding joint meetings of other types with Branches.

**Student Activities.**—Almost all Branches have been active in holding local meetings, and there has been an increased interest in joint meetings and conventions.

During the year, effective Conferences on Student Activities were held in eight Geographical Districts, and both Counselors and Branch Chairmen have been enthusiastic concerning the benefits derived.

Eight very successful Student Conventions were held, four sponsored by Sections, and four by District Committees on Student Activities, and a considerable number of Branches participated.

Through the Conferences, Student Conventions, Section and Branch co-operation, the activities of the Counselors, and the Branch meetings, definite advances have been made in the direction of bringing the students into closer contact with the Institute membership and better understanding of the opportunities for participation in its work.

Student activities have been reported more fully in the JOURNAL since the inauguration of the department for that purpose in January 1927. A revised edition of the "Suggested By-laws for Student Branches," approved by the Board of Directors, and a new pamphlet entitled "Student Activities" were printed.

New Branches were authorized at the University of Louisville and University of Vermont, and the Brown Engineering Society of Brown University became affiliated with the Institute under the provisions of Section 59A of the By-laws.

**Section and Branch Statistics.**—

| | For Fiscal Year Ending | | | |
|---|---|---|---|---|
| | April 30 1921 | April 30 1923 | April 30 1925 | April 30 1928 |
| SECTIONS | | | | |
| Number of Sections | 42 | 46 | 49 | 52 |
| Number of Section Meetings held | 303 | 344 | 386 | 431 |
| Total Attendance | 37,823 | 46,672 | 49,029 | 64,276 |
| BRANCHES | | | | |
| Number of Branches | 65 | 68 | 82 | 96 |
| Number of Branch meetings held | 443 | 503 | 548 | 915 |
| Total Attendance | 21,629 | 26,893 | 27,603 | 44,334 |

**Meetings and Papers Committee.**—The preparation of programs for national conventions and assistance with the programs of regional meetings constituted the principal work of the Meetings and Papers Committee during the year 1927-28. The committee members also, as part of their duty, reviewed miscellaneous papers submitted for publication and assisted the Prize Committee in preliminary selection of papers for prize awards.

The program for the Summer Convention, June 25-29, has been practically completed, and the schedule for the Pacific Coast Convention, August 28-31, has been tentatively arranged. The committee is also working on future meetings.

The total attendance at conventions and regional meetings was 5280, which is 800 above any previous year. The total number of papers presented was 159 including 15 annual reports of technical committees. Many noteworthy contributions to the literature in the various fields of electricity are contained in these papers.

One activity in connection with meetings on which considerable improvement has been made is the printing of advance copies of papers for distribution prior to the meetings. During the last year a much larger proportion of the papers has been printed in time for advance distribution. This improvement has resulted from special efforts exerted in three directions. First, the authors have been urged and persuaded to submit their papers well in advance. Second, the reviewing committees have reduced their time of holding papers while reviewing them. Third, the Editorial Department has obtained closer cooperation with the printers and engravers, thus eliminating delays. Another factor which will undoubtedly assist in this matter is the separation of future meeting dates by at least six weeks, as recently approved by the Board of Directors on the recommendation of the Committee on Coordination of Institute Activities.

**Publication Committee.**—The Publication Committee has paid special attention to the form of Institute publications, resulting in the policy in force since January 1928. The constantly increasing volume of papers presented at Institute meetings each year made some change imperative, as under the former scheme of publication the limit of expense had been reached, and the size of the JOURNAL and TRANSACTIONS had become unwieldy.

The present scheme of publication, which has been described at length in recent issues of the JOURNAL, consists of advance pamphlet copies of complete papers, free to A. I. E. E. members on request; abridgments, not to exceed four pages, of all papers for the JOURNAL; complete papers with discussions in the QUARTERLY TRANSACTIONS.

Five issues of the JOURNAL have been published under the new plan and reports indicate that the abridgments make the JOURNAL a more readable paper than it formerly was for the membership in general; while the requests for complete pamphlet copies are numerous enough to show that this method of providing for the specialists is functioning satisfactorily.

The first number of the QUARTERLY TRANSACTIONS was published early in February and contained the papers for the last quarter of 1927. The second quarterly will be ready for distribution during May and will contain the papers and discussions of the 1928 Winter Convention, which, it should be noted, are thus made available for reference more than a year earlier than was possible with the annual publication plan.

The last volume of Annual TRANSACTIONS, No. XLVI, is completed and will be distributed in May. It includes the papers and discussion for 1927 from January to September and contains 1178 pages.

**Law Committee.**—During the year this committee has considered various proposed amendments to the Constitution of the Institute, the most important of these being for the purpose of authorizing a change in the date of the Annual Meeting from May to the Annual Summer Convention. This change was approved by the Board of Directors and was authorized at a Special Meeting of the Institute held in Chicago in November, 1927. The various amendments as finally approved by the Law Committee and the counsel of the Institute were submitted to the membership with a letter ballot under date of April 2, 1928.

**Coordination Committee.**—The Committee on Coordination of Institute Activities has considered and made recommendations to the Board of Directors upon various matters coming within its jurisdiction under the By-laws.

These matters have included consideration and favorable report to the Board of Directors upon the recommendations made at the conference of officers and Section delegates at the Summer Convention held in Detroit, in June 1927; the overlapping of committee work; the formulation and recommendation to the Directors of a policy regarding the coordination of future national and regional meetings; and the preparation and recommendation, after requesting and receiving the suggestions of District and Section officers, of a schedule of dates and locations of meetings up to the close of 1929. The latter recommendations are fully covered in a report made to the Board of Directors under date of April 3, 1928 and approved by the Board on April 6, as published in full in the May issue of the Institute JOURNAL.

**Standards.**—The Standards Committee has continued actively the revision of existing standards and the preparation of new standards. By new standards are meant standards for types of apparatus and equipment not covered in the 1922 complete edition of Institute Standards. Twenty-six separate sections have been approved by the Board as Institute Standards. Three sections are still in so-called report form, that is, they are available for comment and criticism by the membership of the Institute before final action by the Standards Committee and recommendation to the Board. Eight of the Standards have been approved as American Standard by the American Engineering Standards Committee, but all of the Standards, except those under actual revision, have been submitted for such approval.

At the request of the Board, the Standards Committee has made recommendations for representatives of the Institute on Sectional Committees. The Institute is sole sponsor for six projects, joint sponsor for 15, and has representation on 29 other Sectional Committees under A. E. S. C. procedure. The Standards Committee receives reports from these representatives and makes recommendations to the Board based on such reports.

Spanish translations of eight standards were published by the Bureau of Foreign and Domestic Commerce, Department of Commerce, Washington, D. C., during the year. A folder in English and Spanish, listing all the standards available in the Spanish language, was prepared and widely circulated in the Spanish-speaking countries of South and Central America. Arrangements are also being made with the Bureau of Foreign and Domestic Commerce to make revisions in the Spanish text, when standards are revised.

The committee has continued very close cooperation with the United States National Committee of the

International Electrotechnical Commission. Of the 22 delegates to the Bellagio, Italy, meeting of the Commission (Sept. 1927), 18 are members of the Institute. There has been the closest cooperation between groups of advisers, U. S. N. C., I. E. C., Sectional Committees, Technical Committees, and the Standards Committee.

Several important new projects have been initiated. The formation of a Sectional Committee on definitions in the electrical field, under the sponsorship of the Institute, has been recommended. It is very desirable that there be unification and coordination of definitions in the electrical art and industry. An important and far-reaching resolution, prepared by the Instruments and Measurements Committee, on the relation of the international electrical units to the fundamental absolute units was considered and its adoption recommended to the Board.

**American Engineering Standards Committee.**—Aside from the routine matters on which the Institute delegates to American Engineering Standards Committee have been required to vote, covering such matters as the approval of standards, the delegation has attempted faithfully to serve the larger interests of American Engineering Standards Committee consistently with the policies of the Institute as laid down by the Board of Directors in the reviewing of the status of American Engineering Standards Committee and its readjustment to a changing national emphasis in the matter of standards.

The delegation has felt a primary responsibility in making clear to the other members that the American Institute of Electrical Engineers regards itself as being if not the principal at least one of the more significant influences in the inception of the work of formulating American Electrical Standards and procuring their recognition. It is believed that much has been accomplished in making clear that the American Institute of Electrical Engineers is in sympathy with the purposes and ideals of American Engineering Standards Committee. To this end the delegation has attempted to interpret the Institute to American Engineering Standards Committee and conversely to keep the Board of Directors advised of developments in American Engineering Standards Committee.

The latter organization has during the year, with the strong support of the Institute, entirely revised its methods of procedure in a manner which already has clarified and expedited the process of giving recognition to American standards and is at the present time actively concerned in the matter of a general re-constitution which shall bring the processes of standardization more nearly into coincidence with a changing condition which arises from the more general industrial recognition of the necessity for universally accepted national standards. The Institute representatives are, at the present time, taking an active part in the determination of the lines along which such re-constitution should proceed and it is believed will do so without any conflict with the fundamental purposes of the American Institute of Electrical Engineers.

**U. S. National Committee of I. E. C.**—The work of the United States National Committee of the International Electrotechnical Commission for the past year was very largely centered in preparation for and participation in the Plenary Meeting of the commission which was held in Italy, September 1927. Because of the character of its organization and the large amount of very effective work which was done by the various groups of advisors cooperating with all branches of the industry, delegates of the U. S. National Committee went to the meeting in Bellagio well prepared to put forward the views of the industry in this country in all the various matters with which the commission is concerning itself.

The meetings at Bellagio covered the period from September 3 to 11, during which time the Advisory Committees convened and very substantial progress was made in the work of the commission. This work does not lend itself readily to description in a summarized way largely because it is in different states of completion.

On the occasion of a formal dinner the American delegates presented to the Italian National Committee a bust of Benjamin Franklin on behalf of all of the eighteen visiting nationalities. The presentation was received with words of warmest appreciation.

Following the meetings in Bellagio came a tour offered by the Railway Administration of Italy, and a Plenary Meeting in Rome.

The work of the committee has been actively resumed since the Bellagio Meeting and it is the expectation of the U. S. National Committee that by the time of the next Plenary Meeting of the commission, to be held in the Scandanavian countries in 1930, a large amount of material will be ready for final consideration.

**U. S. National Committee of the International Commission on Illumination.**—The International Commission on Illumination had been scheduled to hold a Plenary Meeting in the United States in the year 1927 but for various reasons it seemed best that this Plenary Meeting should be put off for a year and a series of committee meetings should be held in Europe. Technical Committees of the Commission as well as the Executive Committee were accordingly convened at Bellagio, Lake Como, on the 31st of August and meetings were held on that day and on the 1st and 2nd of September, 1927. At these meetings the U. S. National Committee was represented by the seven delegates.

Apart from the technical matters considered there was brought up the consideration of recommendations of the U. S. National Committee with respect to the scope of the work of the commission. As a result the scope of the commission's work was considerably enlarged so that at the present time there are some fifteen subjects being considered. The Secretariats for these subjects are distributed amongst the various

National Committees, thus distributing the work and throwing an undue burden on none.

The Secretariats assigned to the United States are as follows: Headlights; Factory and School Lighting.

The Executive Committee of the Commission voted to hold the next Plenary Meeting in America in September, 1928, and the U. S. National Committee has been engaged in preparations for this meeting. It seemed to the committee that it would be fitting to request the Illuminating Engineering Society to make the necessary arrangements for this meeting. Such a request was made and accepted and the preparations for the meeting have been coming on actively.

In view of the scope of the meeting, which exceeds somewhat that of previous I. C. I. meetings because of the desire to bring in representatives of nationalities not now represented on the I. C. I., the entire meeting has been designated as an International Illumination Congress.

**Committee on Safety Codes.**—Probably the most important action taken by the committee has been the approval of the set of Standard Rules for the application of the Prone Pressure Method of Resuscitation, which was prepared for universal adoption in this country under the auspices of the United States Public Health Service, with many other organizations cooperating.

The committee also further gave its approval to the Manual of Standard Practice as prepared and approved by the American Gas Association and National Electric Light Association, which includes the rules named above.

The committee is continuing its work in endeavoring to get proper safety activities developed in the Sections and Branches. This work includes the appointment of suitable liaison officers from the National Safety Council; arrangements for cooperation with other bodies in local, community safety meetings.

The work of the Branches naturally is confined largely to suitable activities in the Branches themselves. It is the intent to direct these activities so that the graduating classes will be more fully aware of their responsibilities for accident prevention, and more fully trained in the use of tried safety methods than has been often the case in the past.

Finally, the committee has taken action recommending to the Board of Directors that the Institute offer its support to the National Safety Council in carrying through the Annual Safety Congress for 1928, which is to be held in New York City next October.

**Technical Committees.**—Reports of Technical Committees embracing an outline of the year's work and a summary of progress in the industry will be presented at the Annual Summer Convention and printed in the TRANSACTIONS.

**Membership.**—The following table gives the number of members added to the roll during the year and the number whose affiliations have terminated through resignation, death, or delinquency in dues. The membership total as of May 1, 1928, is 18,265. The slight decrease in total membership, as shown, is due to special causes of a temporary nature, which operated during the year.

| | Honorary | Fellow | Member | Associate | Total |
|---|---|---|---|---|---|
| Membership on April 30, 1927 | 4 | 644 | 2,931 | 14,770 | 18,349 |
| Additions: | | | | | |
| Transferred | | 26 | 255 | | |
| New Members Qualified | | 1 | 77 | 1,503 | |
| Reinstated | | 1 | 12 | 81 | |
| Total | 4 | 672 | 3,275 | 16,354 | 20,305 |
| Deductions: | | | | | |
| Died | | 8 | 20 | 48 | |
| Resigned | | 4 | 26 | 440 | |
| Transferred | | | 17 | 204 | |
| Dropped | | 1 | 48 | 1,164 | |
| Membership April 30, 1928 | 4 | 659 | 3,164 | 14,438 | 18,265 |

**Deaths.**—The following deaths have occurred during the year.

*Fellows:* James R. Craighead, Elmer E. F. Creighton, William C. L. Eglin, Alexander C. Humphreys, James Kynoch, Paul Spencer, Charles Vernier, James J. Wood.

*Members:* Frederick L. Baer, James E. Barker, Louis C. Brooks, Aubrey L. Broomall, Harry L. Brown, Blanchard C. Edgar, Carlo Ferrari, Frank E. Field, James M. Graves, George Ross Green, Charles T. Guildford, Harry E. Hayes, George L. Hedges, Augustus T. Holbrook, Robert M. Lloyd, Allen H. Moore, Michael C. Polivanoff, Ernest E. Schmid, Irving W. Smith, Hugh T. Wreakes,

*Associates:* Jean B. Balcomb, William K. Benz, Ole S. Beagstad, Abel L. Brownrigg, Charles F. Brush, Jr., George A. Buchanan, William C. Chappell, Henry H. Curtis, R. T. Davis, Charles S. Dawson, Charles P. Drake, George Eisenhauer, Charles H. Fisher, Sydney Fisher, Maurice C. Fitzgerald, George H. Gettess, William F. M. Goss, Baxter R. Grier, Edmund M. Hallowell, James W. Harris, Alexander W. Hearne, Harry G. Hopkins, Roy D. Huxley, Frank E. Idell, Johannes Johansen, Senter M. Jones, Paul T. Kamerer, Keijiro Kishi, Arthur R. Leavitt, Basil W. Lee, Archie L. Lewis, Gordon E. McLean, Robert Miller, Otis Sherman Newton, Frederick E. Norman, Ralph M. Obergfell, John L. Phillips, William E. Poole, Fred B. Seem, Frederick G. Simpson, Walter Stumpf, Soichi Takeda, Frank F. Thompson, Howard F. Thurber, Beverley B. Tucker, Thomas A. Wilkinson, Harold P. Williamson, Byron M. Wood.

**Board of Examiners.**—The Examiners have had before them during the past year the question of the comparative number of members of the Institute in the three grades of Associate, Member, and Fellow, and whether the present number in those grades represented a true cross-section of the electrical field with regard to the professional accomplishments of the members and the positions held. A special committee has been authorized by the Directors to consider this entire question. The total number of cases of admission and transfer considered by the Examiners this year is indicated below:

Applications for Admission

| | | |
|---|---|---|
| Recommended for grade of Associate | 1243 | |
| Not recommended | 13 | 1256 |
| Recommended for grade of Member | 78 | |
| Not recommended for admission to this grade | 25 | 103 |
| Recommended for grade of Fellow | 2 | |
| Not recommended for admission to this grade | 1 | 3 |
| Recommended for enrolment as Students | | 1967 |

Applications for Transfer

| | | |
|---|---|---|
| Recommended for grade of Member | 280 | |
| Not recommended for transfer to this grade | 17 | 297 |
| Recommended for grade of Fellow | 21 | |
| Not recommended for transfer to this grade | 3 | 24 |
| Total number of applications considered | | 3650 |

**Institute Prizes.**—At the meeting of the Board of Directors of the Institute of June 23, 1927, recommendations of the Committee on Award of Prizes were approved establishing five National prizes of $100.00 cash and suitable certificates to be awarded yearly as follows: Three First Prizes for (a) Engineering Practise, (b) Theory and Research, (c) Public Relations and Education; and in addition a Prize for Initial Paper and Prize for Branch Paper. The following Regional prizes may also be awarded yearly in each of the ten Geographical Districts, each prize to consist of $25 and suitable certificate, as follows: First Prize, Prize for Initial Paper, Prize for Branch Paper.

The awards for the year 1927 have not as yet been made but the committee's report is expected in May. The presentations will take place at the Denver meeting.

**Scholarships.**—The governing bodies of Columbia University have placed at the disposal of the Institute each year a scholarship in electrical engineering for each class. The awards are made annually by an Institute committee. The scholarships pay $350 toward annual tuition with provision for reappointment. An award for the academic year 1927-28 was made to Walter L. Lawrence.

Complete details governing prizes and scholarships may be obtained by applying to the National Secretary of the Institute.

**Edison Medal.**—The Edison Medal, founded by associates and friends of Thomas A. Edison, is awarded annually by a committee consisting of twenty-four members of the Institute "for meritorious achievement in electrical science, electrical engineering, or the electrical arts." The medal for 1927 was awarded to William D. Coolidge, "for his contributions to the incandescent electric lighting and the X-ray arts." The presentation took place at the Winter Convention of the Institute, February 15, 1928.

**John Fritz Medal.**—The John Fritz Medal Board of Award, which is composed of representatives of the national societies of Civil, Mining, Mechanical, and Electrical Engineers, awarded the twenty-fourth medal to John J. Carty, of New York, "for achievements in telephone engineering." The medal was presented at New York at the Winter Convention of the Institute, February 15, 1928.

**Lamme Gold Medal.**—A bequest was made by the late B. G. Lamme, to cover the cost of an annual award by the Institute of a gold medal, to a member who has shown meritorious achievement in the development of electrical apparatus. The conditions governing the award of the Lamme Gold Medal are now being prepared by a special committee.

**Commission of Washington Award.**—The Washington Award for 1928 was made to Dr. Michael I. Pupin "for devotion to scientific research leading to his inventions which have materially aided the development of long distance telephony and radio-broadcasting."

The award is made annually "to an engineer whose work in some special instance, or whose services in general have been noteworthy for their merit in promoting the public good," by a committee composed of nine representatives of the Western Society of Engineers and two each from the A. S. C. E., the A. I. M. E., the A. S. M. E., and the A. I. E. E.

**Employment Service.**—The employment service which the Institute has maintained for many years is conducted as a cooperative bureau in conjunction with a similar service maintained by the National Societies of Civil, Mining, and Mechanical Engineers under the title, "Engineering Societies Employment Service." In addition to the main office in the Engineering Societies Building, New York, offices have been opened in Chicago in cooperation with the Western Society of Engineers and in San Francisco under similar arrangements with the California Section, American Chemical Society, and Engineers Club of San Francisco. Arrangements have been completed to open a branch office in Denver, Colorado, in cooperation with the Colorado Engineering Society. It is hoped to continue this development from year to year as conditions warrant. The service is supported by the joint contributions of the societies and their individual members who are benefited. As in the past it consists principally in acting as a medium for bringing together the employer and the employee. In addition to the publication of the "Employment Service Bulletin" in the monthly JOURNALS, weekly subscription bulletins are issued for those seeking positions.

**American Engineering Council.**—American Engineering Council, with which the Institute is affiliated, is completing its eighth year as representative of its constituents, at conferences, conventions, on important committees of other organizations, and at Congressional hearings. It now has a membership of 25 national, state, and local engineering societies totalling an individual membership of something over 43,000 professional engineers.

During the past year it has extended aid of a valuable character to over 200 societies and individuals. Council is becoming well known as an authoritative source of information and reference.

Council, however, does not confine itself to such activities but pursues many other projects. It has representatives on such government committees as the Advisory Council to the Board of Surveys and Maps, the Planning Committee of the Division of Simplified Practice, the Committee appointed to draft a Uniform State Mechanics Lien Act, and the several executive committees of the Hoover Conference on Street and Highway Safety. It likewise has representatives on committees formed by other groups, as the U. S. Chamber of Commerce, the National Bureau of Economic Research, the World Congress of Engineers, and the celebration of the 200th anniversary of the birth of George Washington.

The legislative year has been an exceedingly busy and active one.

The Public Affairs Committee is completing the busiest year of its existence. Never before since the establishment of Council have so many bills been introduced into a single session of Congress which have come so directly within the purview of American Engineering Council.

Council has continued its active support of and is hopeful that most of the following measures will be passed during this session of Congress: Newton Bill, calling for an inventory of the water resources of the United States; Parker Bill, providing an equitable status for sanitary engineering and sanitary engineers in the U. S. Public Health Service; Wyant Bill, which assembles the greater part of the civil engineering and construction services of the Government under one government division in the Department of the Interior; Ransdell Bill, which calls for the establishment of a national hydraulic laboratory in the U. S. Bureau of Standards; and the McNary-Woodruff and McNary-McSweeney Bills which provide for a fixed national forestry policy and for an augmented research program by the Department of Agriculture in certain matters pertaining to forestry.

The Council has continued its opposition to the Swing-Johnson Bill; to legislation seeking to grant certain patents to Garabed K. Giragossian, without jurisdiction of the Patent Office; to Government ownership and operation of certain projects, as Muscle Shoals; to any legislation which tends to nullify the Federal Power Commission's jurisdiction.

The year has seen the completion of two studies: Safety and Production; and Street Signs, Signals, and Markings. Safety and Production is now off the press and being distributed. The report on Street Sigsn, Signals, and Markings will be issued in pamphlet form within the next few months. It is expected that the recommendations of the Committee on Street Signs, Signals, and Markings will be adopted as American standard. Legislative activity is now under way which will culminate in the adoption, almost in toto, of the recommendations of Council's Committee as state requirements by the State Legislatures of New York and of New Jersey.

Important special committees which will function throughout the year are Flood Control, Radio Broadcasting, President's Committee on Constitution, By-Laws and Activities of American Engineering Council, Patents, Power, and Program of Research.

The Flood Control Committee has been and will continue to be active in connection with the Mississippi Valley flood problems; the Radio Broadcasting Committee is continuing to render valuable assistance to the Federal Radio Commission; the Patents and Power Committees have been active in connection with numerous pieces of legislation, both desirable and undesirable, which have been before Congress for consideration. The Program of Research Committee is undertaking to establish certain fundamental principles which shall govern future research policies of American Engineering Council.

**United Engineering Society.**—This Society performs for the national societies of Civil, Mining, Mechanical, and Electrical Engineers, certain specific acts which are governed by contracts; the primary function of the United Society being to hold in trust and to administer for these societies the Engineering Societies Building, in which the headquarters of the national societies are located.

Extracts from the annual financial report of the United Engineering Society were published in the March 1928 JOURNAL.

**Engineering Societies Library.**—The library of the Institute is combined with the libraries of the national societies of Civil, Mining, and Mechanical Engineers, administered as the "Engineering Societies Library" under the direction of the Library Board of the United Engineering Society; this board is composed of representatives of each of the four societies referred to above.

In order to place the facilities of the library at the disposal of persons residing at a distance from New York, a Library Service Bureau has been established, and a staff of expert searchers and translators is employed to cover almost any engineering topic, in the following manner: abstracting, translating, bibliographing, statistical searches and reports, searches for patent purposes, copying, preparing reference cards, etc. A lending department is also maintained.

A copy of the annual report of the Engineering Societies Library covering the calendar year 1927, may be obtained by applying to Institute headquarters.

**Engineering Foundation.**—Engineering Foundation is a trust fund established in 1914 by Ambrose Swasey, of Cleveland, Ohio, by gifts to United Engineering Society as a nucleus of a large endowment "for the furtherance of research in science and in engineering, or for the advancement in any other manner of the profession of engineering and the good of mankind." The fund has been generously increased through the gifts of Edward D. Adams and others, and also through bequest under the will of the late Henry R. Towne. It is administered by the Engineering Foundation Board upon which the Institute and other national engineering societies are represented. The Board is a Department of United Engineering Society.

The Foundation has made appropriations for various research projects and has cooperated in others.

The annual report of the Foundation is available in printed form.

**Representatives.**—The Institute has continued its representation upon various national committees and other local and national bodies with which it has been affiliated in past years, and has accepted sponsorship and appointed representatives upon a number of new Sectional Committees of American Engineering Standards Committee. A complete list of representatives is published frequently in the JOURNAL.

**Finance Committee.**—During the year the committee has held monthly meetings, has passed upon the expenditures of the Institute for various purposes, and otherwise performed the duties prescribed for it in the Constitution and By-laws.

Haskins and Sells, certified public accountants, have audited the books, and their report follows:

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Respectfully submitted for the Board of Directors

F. L. HUTCHINSON,

*National Secretary.*

New York, May 18, 1928

HASKINS & SELLS
CERTIFIED PUBLIC ACCOUNTANTS
OFFICES IN THE PRINCIPAL CITIES OF
THE UNITED STATES OF AMERICA
AND IN
LONDON, PARIS, BERLIN, SHANGHAI,
MONTREAL, HAVANA, MEXICO CITY

37 WEST 39TH STREET
NEW YORK

May 17, 1928.

American Institute of Electrical Engineers,
33 West 39th Street,
New York.

Dear Sirs:

We have made a general audit of your accounts for the year ended April 30, 1928, and submit the following exhibits and schedule:

Exhibit

A—Balance Sheet, April 30, 1928.
Schedule 1—Reserve Capital Fund—Securities.

B—Summary of Income and Profit and Loss for the Year Ended April 30, 1928.

WE HEREBY CERTIFY that in our opinion Exhibits A and B, respectively, correctly set forth the financial condition of the Institute at April 30, 1928, and the results of its operations for the year ended that date.

Yours truly,
HASKINS & SELLS

**Exhibit A.**

## Balance Sheet, April 30, 1928

### ASSETS

| | | | |
|---|---|---|---|
| **Real Estate:** | | | |
| One-fourth interest in United Engineering Society's Land, Building, and Building Equipment, 25 to 33 West 39th Street (Depreciation carried on books of United Engineering Society) | | | $493,352.60 |
| **Equipment:** | | | |
| Library—Volumes and Fixtures | | $ 41,298.96 | |
| Works of Art, Paintings, etc | | 3,001.35 | |
| Office Furniture and Fixtures | $27,037.87 | | |
| Less Reserve for Depreciation (including $5,884.29 funded) | 10,316.68 | 16,721.19 | |
| Total Equipment | | | 61,021.50 |
| **Working Assets:** | | | |
| "Transactions," etc | | $ 4,490.75 | |
| Paper and Cover Paper | | 5,245.94 | |
| Badges | | 2,181.12 | |
| Total Working Assets | | | 11,917.81 |
| **Current Assets:** | | | |
| Cash | | $ 12,551.96 | |
| Accounts Receivable: | | | |
| Members—For Dues | | 23,735.68 | |
| Advertisers | | 1,147.00 | |
| Miscellaneous | | 5,457.33 | |
| Accrued Interest on Investments | | 1,994.53 | |
| Total Current Assets | | | 44,886.50 |
| **Funds:** | | | |
| Reserve Capital Fund: | | | |
| Securities—Schedule 1 | | $143,711.88 | |
| Life Membership Fund: | | | |
| Cash | $ 6,438.56 | | |
| Chicago, Burlington & Quincy Railroad Company 4% Bonds, 1958, Registered, Par Value $5,000.00. | 4,868.75 | | |
| Accrued Interest | 33.33 | 11,340.64 | |
| International Electrical Congress of St. Louis—Library Fund: | | | |
| Cash | $ 990.74 | | |
| New York City 4½% Corporate Stock, 1957, Par Value $2,000.00 | 2,204.05 | | |
| New York Telephone Company 4½% Bond, 1939, Registered, Par Value $1,000.00 | 878.75 | | |
| Accrued Interest | 67.50 | 4,141.04 | |
| Mailloux Fund: | | | |
| Cash | $ 2.50 | | |
| New York Telephone Company 4½% Bond, 1939, Registered, Par Value, $1,000.00 | 1,000.00 | | |
| Accrued Interest | 22.50 | 1,025.00 | |
| Lamme Medal Fund: | | | |
| Cash | $ 894.83 | | |
| Baltimore and Ohio Railroad Company 6% Refunding and General Mortgage Series "C" Bond, 1995, Par Value $4,000.00 | 4,330.00 | | |
| Accrued Interest | 100.00 | 5,324.83 | |
| Depreciation of Furniture and Fixtures Fund: | | | |
| Cash | $ 871.79 | | |
| Cleveland Union Terminals Company 5% Sinking Fund Series "B" Gold Bonds, 1973, Registered, Par Value $5,000.00 | 5,012.50 | 5,884.29 | |
| Total Funds | | | 171,427.68 |
| Total | | | $782,606.09 |

### LIABILITIES

| | | |
|---|---|---|
| **Current Liabilities:** | | |
| Accounts Payable | $ 14,182.09 | |
| Dues Received in Advance | 2,772.07 | |
| Entrance Fees and Dues Advanced by Applicants for Membership | 556.85 | |
| Subscriptions for "Transactions" Received in Advance | 79.00 | |
| Total Current Liabilities | | $ 17,590.01 |
| **Fund Reserves (Not Including Depreciation Reserves):** | | |
| Reserve Capital Fund | $143,711.88 | |
| Life Membership Fund | 11,340.64 | |
| International Electrical Congress of St. Louis—Library Fund | 4,141.04 | |
| Mailloux Fund | 1,025.00 | |
| Lamme Medal Fund | 5,324.83 | |
| Total Fund Reserves (Not Including Depreciation Reserves) | | 165,543.39 |
| **Surplus**, Per Exhibit "B" | | $599,472.69 |
| Total | | $782,606.09 |

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

### SUMMARY OF INCOME AND PROFIT AND LOSS FOR THE YEAR ENDED APRIL 30, 1928

**Exhibit B.**

| | | | |
|---|---|---|---|
| **Income:** | | | |
| Dues | | *$227,666.66 | |
| Students' Fees | | 10,917.00 | |
| Entrance Fees | | 15,525.00 | |
| Transfer Fees | | 1,460.00 | |
| Advertising | | 82,978.19 | |
| Journal Subscriptions | | 10,164.38 | |
| "Transactions" Subscriptions | | 19,503.19 | |
| Miscellaneous Sales | | 10,126.09 | |
| Badges Sold | $ 4,290.65 | | |
| Less Cost | 3,505.08 | 785.57 | |
| Interest on Securities in Reserve Fund | | 6,874.20 | |
| Interest on Bank Balances | | 1,220.69 | |
| Total | | | $387,220.97 |
| **Expenses:** | | | |
| Publications: | | | |
| Journal | $103,497.42 | | |
| "Transactions" | 31,250.50 | | |
| Year Book | 7,626.27 | | |
| Miscellaneous | 3,778.94 | $146,153.13 | |
| Institute Meetings | | 25,953.90 | |
| Administrative Expenses | | 59,864.70 | |
| Sections | | 31,119.94 | |
| Membership | | 7,454.69 | |
| Standards | | 8,103.92 | |
| Finance | | 350.00 | |
| Headquarters | | 1,507.70 | |
| Code Committee, | | 60.00 | |
| Technical Committees | | 192.45 | |
| Edison Medal | | 308.10 | |
| Law Committee (Revision of Constitution) | | 1,019.39 | |
| Geographical Districts Expense: | | | |
| Traveling expense: | | | |
| Executive Committee | $ 1,523.69 | | |
| Vice-Presidents | 973.99 | | |
| Speaker's Bureau | 64.26 | | |
| Best Paper Prize | 100.00 | | |
| First Paper Prize | 75.00 | 2,736.94 | |
| Branch Activities: | | | |
| Meetings | $ 537.26 | | |
| Traveling Expense—Counsellors. | 5,286.33 | | |
| Salaries and Miscellaneous | 2,435.65 | 8,259.24 | |
| Forward | | $293,084.10 | $387,220.97 |

| | | | |
|---|---|---|---|
| **Total Income—Forward** | | | $387,220.97 |
| **Expenses—(Forward)** | | $293,084.10 | |
| American Engineering Standards Committee | | 1,500.00 | |
| International Electrotechnical Commission | | 1,521.16 | |
| United States National Committee of International Commission on Illumination | | 300.00 | |
| Louvain Memorial | | 929.27 | |
| President's Special Appropriation | | 357.24 | |
| Board of Directors—Traveling Expenses | | 3,668.46 | |
| National Nominating Committee, Traveling Expenses | | 979.03 | |
| Institute Representatives—Traveling Expenses | | 178.27 | |
| Honorary Secretary | | 4,000.00 | |
| John Fritz Medal | | 417.53 | |
| Engineering Societies Library—Maintenance | | 8,729.14 | |
| United Engineering Society Assessment | | 5,711.04 | |
| American Engineering Council | | 17,725.00 | |
| Engineering Societies Employment Service | | 1,635.00 | |
| International Annual Tables | | 100.00 | |
| Institute Prizes | | 400.00 | |
| Total | | | 341,235.24 |
| **Net Income** | | | $ 45,985.73 |
| **Profit and Loss Credits:** | | | |
| Adjustment of Inventories: | | | |
| "Transactions" | $ | 669.25 | |
| Library Volumes and Fixtures | | 691.12 | 1,360.37 |
| **Gross Surplus for the Year** | | | $ 47,346.10 |
| **Profit and Loss Charges:** | | | |
| Uncollectible Dues and Members' Charges Written Off | | $ 12,110.35 | |
| Furniture, Fittings and Equipment Scrapped or Sold—Net | | 117.23 | |
| Provision for Depreciation of Furniture and Fixtures | | 1,343.66 | |
| Total | | | 13,571.24 |
| **Surplus for the Year** | | | $ 33,774.86 |
| **Surplus, May 1, 1927** | | $602,756.01 | |
| †Less Transferred to Capital Fund Reserve in Accordance with Resolution of the Board of Directors | | 37,058.18 | 565,697.83 |
| **Surplus, April 30, 1928** | | | $599,472.69 |

*Includes $103,724.00 allocated to subscriptions for the JOURNAL and TRANSACTIONS.

†Includes authorized investments for appropriation year beginning October 1, 1926 and part of authorized investments for ensuing year.

## AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

### RESERVE CAPITAL FUND—SECURITIES

### APRIL 30, 1928

EXHIBIT A.
SCHEDULE NO. 1.

| | Par Value | Book Value |
|---|---|---|
| RAILROAD BONDS: | | |
| Baltimore and Ohio Railroad Company 4½% Convertible Gold Bonds, Due 1933, Registered | $10,000.00 | $ 9,387.50 |
| Baltimore and Ohio Railroad Company 6% Refunding and General Mortgage Series "C" Bonds, Due 1995, Registered | 8,000.00 | 8,940.00 |
| Central of Georgia Railway Company 5½% Refunding and General Mortgage Bonds, Due 1959, Registered | 5,000.00 | 5,283.75 |
| Chicago and Erie Railroad Company 5% First Mortgage Gold Bonds, Due 1982, Registered | 1,000.00 | 1,105.00 |
| Chicago, Burlington & Quincy Railroad Company 5% First and Refunding Mortgage Series "A" Gold Bond, Due 1971, Registered | 1,000.00 | 1,010.00 |
| Chicago, Terre Haute & Southeastern Railroad Company 5% First and Refunding Mortgage Gold Bonds, Due 1960 | 8,000.00 | 7,940.00 |
| Florida East Coast Railway Company 5% First and Refunding Mortgage Series "A" Gold Bonds, Due 1974, Registered | 10,000.00 | 9,818.75 |
| Great Northern Railroad Company 5½% General Mortgage Series "B" Gold Bonds, Due 1952, Registered | 10,000.00 | 9,847.50 |
| St. Louis, San Francisco Railway Company 5% Prior Lien Mortgage Series "B" Bonds, Due 1950, Registered | 6,000.00 | 5,497.50 |
| Southern Railway Company 5% First Consolidated Mortgage Gold Bonds, Due 1994, Registered | 1,000.00 | 980.00 |
| The New York Central Railroad Company 5% Refunding and Improvement Mortgage Series "C" Bonds, Due 2013, Registered | 6,000.00 | 5,742.50 |
| The Pennsylvania Railroad Company 4½% General Mortgage Series "A" Gold Bonds, Due 1965, Registered | 5,000.00 | 5,130.00 |
| Total | $71,000.00 | $70,682.50 |
| PUBLIC UTILITY BONDS: | | |
| Consolidated Gas Company of New York 5½% Gold Debentures, Due 1945, Registered | $5,000.00 | $ 5,187.50 |
| Duquesne Light Company 4½% First Mortgage Series "A" Gold Bonds, Due 1967, Registered | 3,000.00 | 2,970.00 |
| Pacific Gas & Electric Company 5½% First and Refunding Mortgage Gold Bonds, Due 1952, Registered | 5,000.00 | 5,137.50 |
| The American Telephone and Telegraph Company 5% Gold Debentures Sinking Fund, Due 1960, Registered | 15,000.00 | 14,625.00 |
| The Detroit Edison Company 6% First and Refunding Mortgage Series "B" Gold Bonds, Due 1940, Registered | 5,000.00 | 5,178.13 |
| Total | $33,000.00 | $33,098.13 |
| INDUSTRIAL BONDS | | |
| American Smelting and Refining Company 5% First Mortgage 30-Year Gold Bonds, Due 1947, Registered | $9,000.00 | $9,085.00 |
| American Smelting and Refining Company 6% First Mortgage Bonds, Due 1947 | 3,000.00 | 3,241.25 |
| Bethlehem Steel Company 5% Purchase Money and Improvement Mortgage 20-Year Sinking Fund Gold Bonds, Due 1936, Registered | 5,000.00 | 5,033.75 |
| New York Steam Corporation 6% First Mortgage Gold Bonds, Due 1947, Registered | 10,000.00 | 10,837.50 |
| The Western Electric Company 5% Bonds, Due 1944 | 10,000.00 | 9,818.75 |
| United States Rubber Company 5% First and Refunding Mortgage Series "A" Bonds, Due 1947 | 2,000.00 | 1,915.00 |
| Total | $39,000.00 | $39,931.25 |
| Total | $143,000.00 | $143,711.88 |

# Application of Wound Type Current Transformers Installed in High-Voltage Oil Circuit Breaker Tanks

BY J. C. REA[1]

Associate, A. I. E. E.

*Synopsis.—Wound type current transformers installed in the tanks of high-voltage oil circuit breakers have been in operation for many years. The experience gained during this period has resulted in fairly clear definitions as to the types of installations to which they are best suited, and to designs of transformers which are highly reliable. The purpose of this paper is to present a brief history of some of the developments leading up to the present application of wound type current transformers in circuit breakers and to indicate some of the conditions under which they offer special advantages.*

* * * * *

IN the early stages of the electric power industry the oil circuit breaker made its appearance as a solution of the problem of interrupting circuits under load and it was not surprising that efforts were soon made to develop automatic mechanisms which would cause the circuit breaker to open itself on over-current. Some of the earliest forms of devices for performing this duty took the form of solenoid coils connected in series with the circuit controlled by the circuit breaker. These coils acted as electromagnets in a mechanism which was designed to release the operating mechanism of a circuit breaker when a predetermined amount of current flowed through the series coil. The operating mechanism would then throw the circuit breaker to the open position.

A device of this nature was manufactured in 1910 for installation on indoor circuit breakers where it was unnecessary to protect it from the weather. The series coil was mounted on the top of the oil circuit breaker bushing and the motion of the electromagnet was transmitted to the control mechanism through a glass tube which served to insulate the electromagnet from the control mechanism. A further step in the development of this device was to provide for its protection from the weather when used in outdoor oil circuit breakers. This was accomplished by moving the series trip coil to the inner end of the entrance bushing where it operated submerged in oil.

The series trip coil was mounted on the lower end of the bushing. An insulating plate was bolted between the lower end of the bushing conductor and the support for the breaker contact. The series trip coil was connected across this insulating member so that the current flowing through the breaker passed through the trip coil.

The motion was transmitted from the electromagnet to the control mechanism by means of a vertical insulating rod which connected to a lever on a shaft running between the three phases of the circuit breaker. This shaft when rotated released the opening mechanism. Devices of this nature all had the serious defect of requiring very delicate adjustments because the amount of energy available was very small. They also lacked a satisfactory means for varying the time delay.

These defects were readily overcome by the use of current transformers connected to suitable relays. The desired time delay characteristics were obtainable with this combination and additional features such as differential protection, reverse power control, etc., could also be obtained. The current transformers, however, in many cases added a very considerable item of expense to the installation, particularly in the higher voltages.

The use of the entrance bushing on the oil circuit breaker offered a means to provide insulation for the primary circuit of the current transformer, eliminating one of the heaviest items of expense in connection with its use. This means was used either by applying a bushing type transformer in which the primary winding was formed by the conductor passing through the bushing, or a transformer with a primary coil wound on the core and mounted in the oil circuit breaker tank.

In the case of the bushing type transformer no change was required in the conducting parts of the oil circuit breaker in order to pass the primary current through the current transformer.

In applying the wound-type current transformer inside the circuit breaker tank it was necessary to insert the primary coil in series with the conducting parts in the breaker.

## EARLY FORMS OF TRANSFORMERS

In an early form of transformer of this type the primary coil was provided with a bracket which formed one of the leads and was located at the lower end of the bushing. The transformer was arranged with two equal primary windings which could be connected by means of links into either a series or parallel connection so as to obtain two ratios. The bracket lead was fastened to one of the contact members in the oil circuit breaker and formed a partial support for the transformer. The other end of the primary winding

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[1] Chief Engineer, Pacific Electric Mfg. Co., San Francisco, Calif.

*Presented at the Northeastern District No. 1 Meeting of the A. I. E. E., New Haven, Conn., May 9-12, 1928.*

was connected to the conductor at the lower end of the entrance bushing. An insulating plate, bolted between the lower end of the bushing conductor and the support for the breaker contact, caused the current to flow through the primary coil.

As this transformer was designed for use with circuit breakers having dimensions already established, it was necessary to make the primary coil as small as possible and to aid in obtaining this result the secondary coil was placed on the leg of the core opposite to that on which the primary coil was located. This construction not only permitted a small primary coil to be used but also enabled the insulation to be split into two sections. The core was given an equal amount of insulation both from the primary and the grounded secondary coil so that the dielectric stress on the insulation at the primary coil was considerably reduced from that which would have existed if all of the insulation had been applied at one point. The secondary coil leads were brought out along a bracket connection which was built into the secondary coil and which aided in supporting the transformer by being fastened to the top cover of the oil circuit breaker. Transformers of this type were applied to oil circuit breakers ranging from 22,000 to 110,000 volts. They were used for tripping purposes and for operating indicating ammeters for which they were very satisfactory.

The principal reason for the use of these transformers rather than bushing type transformers was to take care of the tripping of high-voltage oil circuit breakers where the current at which tripping was desired was so low that satisfactory performance could not be obtained with bushing type transformers. The accuracy of ratio and phase angle of these transformers with wound primary coils was not sufficient to permit their application to metering. The placing of the primary and secondary coils on the opposite sides of the core also caused a high leakage flux which gave the transformers rather poor characteristics on heavy overloads. This interfered with their application to differential protection of transformer banks.

These weaknesses were not easily remedied because of the space limitations which were imposed on the transformer, due to its being mounted in the tank of the oil circuit breaker. The characteristics obtained and the very material saving in cost over externally mounted transformers made this type of equipment of distinct advantage for many installations.

Further development was made possible by increasing the space available inside of the tanks, permitting the physical dimensions of the transformer to be increased. Improved electrical characteristics were obtained by mounting the primary and secondary coils concentrically upon one leg of the core and increasing the number of ampere-turns and cross-section of core. The characteristics thus obtained made the transformer suitable for metering. The mechanical strength of the transformer as a unit, and also of its mounting in the oil circuit breaker, were also greatly improved by this construction.

The insulation between the primary and secondary coils presents a rather unusual problem because of the possibility of the transformer being operated, at times, in oil of reduced dielectric strength. It is also necessary to provide for a possible accumulation of carbon and other deposits which may adhere to the surface of the insulation.

A type of construction for the major insulation, which has proved highly satisfactory, consists of concentric tubes of laminated phenol compound supported on rings of the same material. Shoulders are turned on the tubes and the supporting rings are pressed against them so that the tubes cannot slip along their axis. The free circulation of the oil between the tubes is insured by perforating the supporting rings. This construction provides for a very long leakage path between the primary coil and ground.

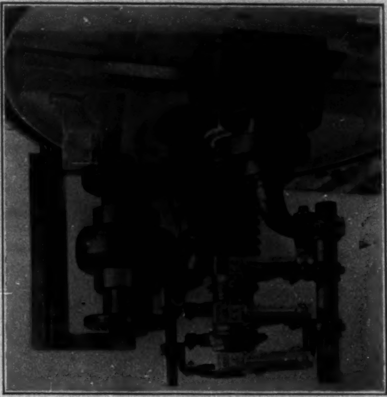

FIG. 1—73-KV. OIL CIRCUIT BREAKERS WITH MODERN WOUND TRANSFORMER

Additional leakage surface is obtained by applying a porcelain tube with a corrugated flange at each end of the Bakelite insulating tube.

## MODERN DESIGNS OF TRANSFORMERS

Figs. 1 and 2 show typical transformers of this construction. The outer coil is the primary which in the transformer illustrated is wound in two sections. Links are provided to permit the sections to be connected, either in series or parallel to obtain two different ratios. The secondary coil is wound on a tube which fits against the core, directly under, and concentric with the primary coil. The secondary leads can be seen, running out to the secondary terminal block at the top of the transformer. The symmetrical arrangement of the coils limits the mechanical forces, due to heavy primary currents, to a minimum.

The mounting of a current transformer in an oil circuit breaker tank calls for particular care because of the mechanical shocks to which the transformer is subjected during the interruption of the circuit by the oil circuit breaker. It has been found that if very substantial support is given to the core of the transformer it will withstand these shocks without sustaining any injury.

Fig. 1 shows a typical mounting of one of these transformers in a multiple-break oil circuit breaker of the rotary type. The core is rigidly held by a bracket which is secured to the cover of the oil circuit breaker. The primary coil is in turn fastened to the lower end of the entrance bushing by means of heavy copper links. The location of the transformer relative to the contacts of the breaker is such that it is at no time endangered by proximity to the arcs, which are drawn upon opening the breaker. In extreme cases, where the number of instruments to be operated exceeds the capacity of one transformer, two of these transformers can be mounted in each phase of the oil circuit breaker. In this case one transformer is applied to each of the entrance bushings.

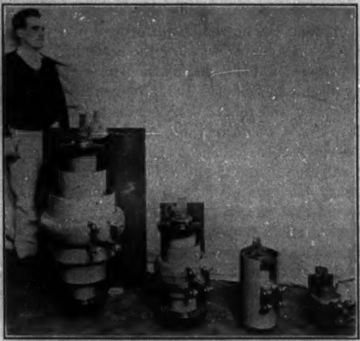

Fig. 2—Comparison of 132-Kv., 73-Kv., 37-Kv., and 25-Kv. Transformers

In some of the earlier transformers of this type trouble was experienced due to surges causing a failure of the insulation between turns in the primary coil. Various protective devices were tried. It was found that by applying very generous insulation between turns on the primary all trouble from this source was eliminated and that protective devices to shunt the surges across the primary coil were unnecessary.

A line of transformers has been developed to cover voltages from 25 kv. to 132 kv. The general construction of these transformers is fairly uniform for the entire range of voltages. Fig. 2 shows the relative size of some of these transformers. The smallest transformer shown is rated at 25 kv. The next larger transformer is a special design and is provided with a cylindrical barrier around the primary coil to permit its installation in a 37-kv. circuit breaker which has a very limited space for the transformer. The third transformer is for mounting in a 73-kv. oil circuit breaker, and the largest one is for mounting in a 132-kv. oil circuit breaker.

This type of transformer has been developed to cover the range of ratios from 5/5 up to 400/5. The primary ampere turns on the lower ratio transformers is approximately 1000, while on the higher ratios 1200 ampere-turns are used. This variation in ampere-turns is brought about by the necessity of providing for the additional insulation in the lower ratio primary coils, which have a large number of turns. The characteristics of the transformers are only slightly affected by this variation in the number of ampere-turns for the different ratios.

## Applications

The application of wound type current transformers in the tanks of oil circuit breakers is particularly advantageous in meeting two distinctly different requirements. One of these cases is where it is necessary to operate watt-hour meters for measuring small amounts of power, where the required accuracy cannot be obtained from bushing type transformers. The second use to which these transformers can be very advantageously applied is to operate tripping relays where the primary current is low and the secondary burden on the transformer is high.

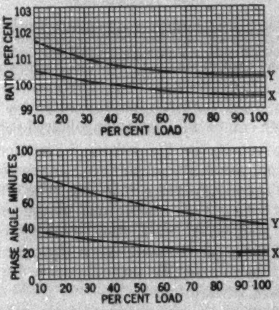

Fig. 3—Characteristics of Wound Transformer

X 2.5 Volt-amperes, 90 per cent power-factor burden
Y 15 Volt-amperes, 90 per cent power-factor burden

For the first case, Fig. 3 shows the ratio and phase-angle curves obtained with this type of wound transformers when operating with burdens of 0.1 ohm resistance 0.13 $\mu$ h. or approximately 2½ volt-amperes, 90 per cent power factor, and of 0.6 ohms resistance 0.7 μ h. or approximately 15 volt-amperes, 90 per cent power factor. These curves are characteristic for the type of transformers herein illustrated over their total range of 5/5 ratio to the upper limit of 400/5 ratio. Where extreme accuracy is needed the ratios can be adjusted by turn compensation to get zero error at any per cent of primary load desired. This is accomplished by the use of two parallel secondary windings having an unequal number of turns. By choosing a suitable combination of turns for these secondary coils, the ratio for a given primary current and burden can be adjusted to any desired value.[2]

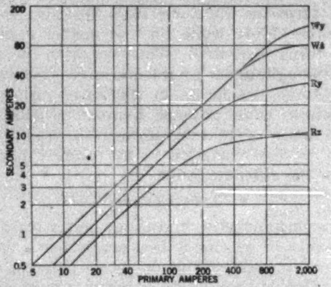

FIG. 4—COMPARISON OF 50.5 RATIO, BUSHING, AND WOUND TYPE TRANSFORMERS

| | |
|---|---|
| W Y | Wound transformer 15 volt-amperes burden |
| W Z | Wound transformer 50 volt-amperes burden |
| R Y | Bushing transformer 15 volt-amperes burden |
| R Z | Bushing transformer 50 volt-amperes burden |

For the second case, Fig. 4 shows the relation between primary and secondary amperes of a conventional 50/5 ratio (10 secondary turns) bushing type transformer and of a wound type transformer of the same ratio. A rating somewhat below that generally considered the minimum for bushing type transformers was chosen so as to magnify the differences between the two types of transformers.

The effect of the distribution of the primary and secondary windings relative to the core of bushing type transformers has been investigated by the Committee on Protective Devices. (JOURNAL of A. I. E. E., August 1927.) Their report shows that a minor error may be caused by an unsymmetrical distribution of the primary and secondary windings. In order to avoid any error from this cause the curves shown in Fig. 4 were taken from a bushing type transformer in which the secondary turns were evenly distributed around the core, and the primary was carefully centered. The curves are shown for burdens of approximately 15 volt-amperes and 50 volt-amperes.

A point that is occasionally overlooked in the application of induction type over-current relays to current transformers is the excessively high burden which they impose on the transformer when they are connected on the low current taps. A type of relay frequently used with bushing type current transformers has a nominal rating of 2-volt-amperes at the tap current. If such a relay is connected to the transformer and operated on the two ampere tap the impedance of the relay alone is approximately equivalent to a burden of 12.5-volt amperes at 5 amperes secondary current of the transformer.

The usual installation of high-voltage oil circuit breakers, requires a considerable length of wire to be run between the current transformers and the relays. Using No. 10 copper wire for the secondary leads, the volt-ampere burden added by the wire is approximately five volt-amperes for each 100 ft. of distance between the transformer and relay. The curves marked *W Y* and *R Y* in Fig. 4 would be those resulting from the use of a two-volt ampere induction type relay connected on the two ampere tap and mounted 50 ft. from the oil circuit breaker. Using a 50/5 ratio transformer it would be expected that the relay would trip the breaker at a minimum of 20 amperes primary current. However, the chart shows that while this would be true with the wound type transformer it would require a minimum of 30 amperes primary current to operate the relay from the bushing type current transformer. Approximately the same burden would be obtained with a 12-volt-ampere relay connected on the five ampere tap, or a 17-volt-ampere relay connected on the six ampere tap, when either relay is located 50 ft. from the current transformer.

The curves marked *W Z* and *R Z* are those obtained with a secondary burden of 50 volt-amperes, 50 per cent power factor. Approximately this amount of burden would be imposed by a 2-volt-ampere relay connected on the one ampere tap or a 17-volt-ampere relay connected on the 3-ampere tap, either of these being located 50 ft. away from the circuit breaker. In this case the bushing type transformer would require more than twice the primary current to operate the relay than that required by the wound type current transformer.

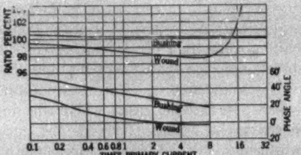

FIG. 5—400 TO 5 RATIO, WOUND, AND BUSHING TRANSFORMERS

Burden 2.5 volt-amperes, 90 per cent power factor

It will also be seen that the ratio of the bushing type transformer varies considerably throughout the range of primary currents and that it becomes very bad at from five to eight times normal current, whereas the wound type transformer has a very small error until the primary current rises to around 20 times normal. This characteristic of the wound type transformer makes it particularly suitable for use on differential protection of transformer banks where the characteristics of the current transformers on both sides of the bank must be carefully matched in order to prevent the operation of the relays on heavy through short circuits.

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[2] Patent No. 1,550,906.

The upper limit of ratios at which it is desirable to apply the wound type current transformer in circuit breaker tanks is fixed by two considerations. The one is a mechanical, and the other an electrical limitation. The duty required of the circuit breaker for rupturing heavy currents usually varies somewhat in proportion to the current which will normally be carried by the breaker. The mechanical strains placed on the transformer are greatly increased where the circuit breaker is used to interrupt very heavy currents.

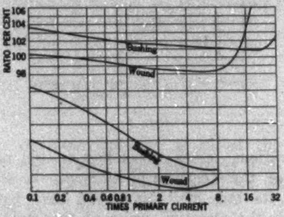

FIG. 6—400 TO 5 RATIO, WOUND, AND BUSHING TRANSFORMERS

Burden, 15 volt-amperes, 90 per cent power factor

This means that even though transformers might be built for heavier primary currents than 400 amperes, their installation in circuit breakers, which are required to carry larger amounts of current, would in many cases be hazardous, because of the severe shocks to which they would be subjected under short circuits and the heavy mechanical forces which would be imposed on them by the explosion when the breaker interrupts the circuit. A second limitation places the 400/5 ratio as a reasonable upper limit for these transformers, because the accuracy of a bushing type transformer of this ratio is approximately as good as that of the wound type transformer.

Figs. 5, 6, and 7 show the comparison between ratio and phase-angle curves of a conventional 400/5 ratio bushing transformer and of the wound type transformer of the same ratio. The curves have been plotted on semi-logarithmic scale so as to condense the portion of the chart beyond full load primary current. The curves in each case were taken without compensating the transformers for the particular burden. This permits direct comparison to be made from one chart to the other to observe the effect of changing the secondary burden on either transformer. These curves show that for a very low burden the bushing type transformer has a better ratio but poorer phase angle than the wound transformer, and that if the burden is increased the wound type transformer has much better characteristics than the bushing type.

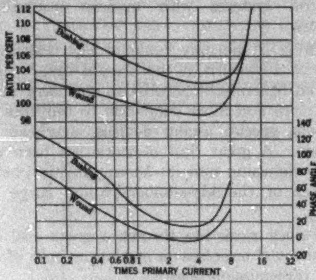

FIG. 7—400 TO 5 RATIO, WOUND, AND BUSHING TRANSFORMERS

Burden, 50 volt-amperes, 50 per cent power factor

## CONCLUSIONS

1. Experience has shown that wound type transformers can be safely installed in the tanks of high-voltage circuit breakers, in many cases, at a very substantial saving of cost over externally mounted transformers.

2. For heavy secondary burdens these transformers can be built to give characteristics that are much better than those of bushing type transformers where the ratios are less than 400/5.

3. For light burdens the wound type transformers offer a means of obtaining characteristics which are suitable for metering at low ratios where bushing type transformers would be entirely unsatisfactory.

# Relation between Transmission Line Insulation
## and Transformer Insulation

BY W. W. LEWIS[1]
Member, A. I. E. E.

DURING the past few years, the great majority of overhead transmission systems in this country have grounded the neutral either solidly or through a moderate resistance.[2] Overvoltages due to arcing grounds on such systems are practically absent. Overvoltages due to switching are in general no longer feared on systems with modern insulation and apparatus.

Lightning is the only cause of high voltage which gives serious concern at the present time.[3] In order to combat lightning, transmission engineers have been adding more and more insulation to the lines as well as various special arcing devices, overhead ground wires, etc. A great deal of work has been done in studying lightning and its accompanying phenomena by means of the klyodonograph and surge voltage recorder.[4]

Laboratory work has thrown a great deal of light on the effect of impulses on insulation, both of apparatus and transmission lines.[5]

The question now arises as to whether, in the light of present knowledge, we can design a transmission line and its connected apparatus so that they will be reasonably safe against breakdown and interference to service due to lightning. Let us first examine the data upon which such a design shall be based.

Sixty-cycle flashover tests on insulators have been made on strings of various numbers of disks. Most of these tests have been made on standard 10-in. disks, spaced 5¾ in. apart. It has been found that the flashover value when plotted against length of string in inches, gives a straight line on log-log paper. The length of string is the spacing per disk times the number of disks. The curve may also be used for insulators of other spacings not differing greatly in proportions from the 10-in. disk spaced 5¾ in. apart. In this case, it is only necessary to multiply the spacing per disk by the number of disks, and enter the curve with the total distance. Table I gives the length of string and 60 cycle flashover for strings of 10 in. disks spaced 5¾ in. apart. The flashover values are plotted against number of disks on Fig. 1.

The impulse flashover of such insulator strings assumes various values, depending on the nature of the impulse, the steepness of its front, the slope and length of its tail, etc. Numerous tests have been made with the standard wave of the High-Voltage Laboratory at Pittsfield on insulator strings of various lengths, and these tests have been repeated with a great deal of consistency.

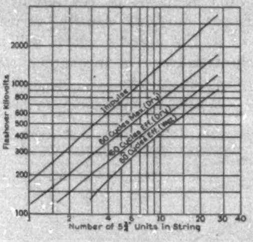

FIG. 1

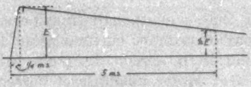

FIG. 2

The Pittsfield wave is a single impulse with a very steep front, rising to its crest value in approximately one-quarter microsecond or less, (depending on the load on the test set), and then decreasing to 50 per cent of the crest value in approximately five microseconds, *i. e.*, the portion of the wave above 50 per cent crest value is approximately one mile in length. This wave is represented in Fig. 2.

The manner of making the tests is to impress on the insulator string such a voltage that the arc-over takes place somewhere on the tail of the wave. The actual

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1. Central Station Engineering Dept., General Electric Co., Schenectady, N. Y.

2. *Present Day Practises in Grounding Transmission Systems*, Report of Subcommittee on Grounding of Protective Devices Committee, TRANS. A. I. E. E., Vol. 42., 1923, p. 753.

3. *Lightning and Other Experience with 132-Kv. Steel Tower Transmission Lines*, Sindeband and Sporn, TRANS, A. I. E. E., Vol. 45, 1926, p. 770.

*1926 Lightning Experience on 132-Kv. Transmission Lines*, P. Sporn, 1928. A. I. E. E. Quarterly TRANS. No. 2.

*Recent Investigation of Transmission Line Operation*, J. G. Hemstreet, TRANS. A. I. E. E., Vol. 46, 1927., p. 835.

4. *Klydonograph Surge Investigations*, Cox, McAuley, and Huggins, TRANS, A. I. E. E., Vol. 46, 1927, p. 315.

*Measurement of Surge Voltages on Transmission Lines Due to Lightning*, Lee and Foust, TRANS, A. I. E. E., Vol. 46, 1927, p. 339.

5. *Lightning and Other Transients on Transmission Lines*, F. W. Peek, TRANS. A. I. E. E., Vol. 43, 1924, p. 1205.

*Presented at the Northeastern District No. 1 Meeting of the A. I. E. E., New Haven, Conn., May 9-12, 1928.*

flashover value is determined by adjusting a sphere-gap in multiple with the insulator string until about one-half of the flashovers take place over the insulator string and one-half over the sphere-gap. The setting of the sphere-gap is then taken as a measure of the flashover potential. The values thus determined (Table I), plotted against length of string, again form a straight line on log-log paper somewhat above the 60-cycle values (Fig. 1).

The ratio of the impulse flashover to the 60-cycle maximum or crest flashover is called the impulse ratio.[6] It will be seen that this varies from approximately 1.5 to 2 within the range of the curves. A fair average would be 1.8.

TABLE I

FLASHOVER OF INSULATOR STRINGS BASED ON 10-IN. DISKS SPACED 5¾ INCHES

| No. disks | Length of string inches | 60-cycle arc-over kv. eff. | Impulse arc-over kv. max. |
|---|---|---|---|
| 3 | 17.25 | 200 | 470 |
| 4 | 23. | 255 | 610 |
| 5 | 28.75 | 305 | 750 |
| 6 | 34.5 | 355 | 890 |
| 7 | 40.25 | 400 | 1020 |
| 8 | 46. | 445 | 1150 |
| 9 | 51.75 | 490 | 1280 |
| 10 | 57.5 | 540 | 1410 |
| 11 | 63.25 | 580 | 1520 |
| 12 | 69. | 620 | 1660 |
| 13 | 74.75 | 660 | 1780 |
| 14 | 80.5 | 700 | 1900 |
| 15 | 86.25 | 745 | 2020 |
| 16 | 92. | 785 | 2140 |
| 17 | 97.75 | 820 | 2260 |
| 18 | 103.5 | 865 | 2380 |

If an extremely high potential is applied as compared with the flashover value of the insulators on the tail of the wave, then flashover will take place on the front of the wave. For the particular wave we have been discussing, it has been found that the flashover values thus found are very consistently about 20 per cent greater than the values determined when the flashover takes place on the tail of the wave. For other waves, of course, there may be a somewhat different relation between flashover on the front and tail of the wave.

In actual practise, flashover of insulator strings may take place either on the front of the wave or on the tail of the wave, and sometimes even on the crest of the wave. In case flashover takes place on the front of the wave, then only a small portion of the wave passes on to the rest of the line and station apparatus (Fig. 3A.) When flashover takes place on the tail of the wave, a longer portion of the wave passes on, and as this represents a greater amount of energy, the wave is capable of doing considerable damage if it reaches station apparatus (Fig. 3B). If the value of the wave is not quite sufficient to flash over the insulator string either on the front or the tail, then the full wave will pass on toward the station (Fig. 3C). In each case, there may be considerable attenuation along the line before the wave reaches the station.

Some data have been taken on oil-filled bushings and pedestal type insulators, such as used on disconnecting switches. These data indicate an impulse ratio slightly higher than for line insulators. There appears to be a similar difference of approximately 20 per cent between the flashover value on the tail of the wave and on the front of the wave with the particular wave used in the tests.

During the past few years, numerous data have been accumulated by means of the klydonograph and surge voltage recorder, which has indicated the maximum voltage to be expected on transmission lines with present standards of insulation to be in the neighborhood of 10 to 12 times the crest value of the line to neutral voltage of the system.[4]

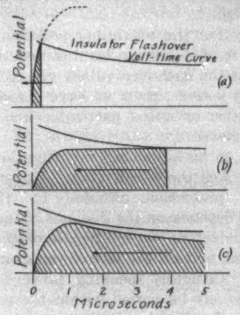

FIG. 3

Table II gives the average number of insulator disks used on actual systems, also the minimum and maximum number of disks for the various standard system voltages, the data being compiled mainly from the *Electrical World Supplement* of January 3, 1925. The impulse flashover value is given also. From this table it will be noted that the impulse flashover value

TABLE II

INSULATION OF ACTUAL LINES

| System voltage kv. | Crest value line to neut. voltage kv. | No. of insulator disks | | Impulse flashover kv. | Ratio impulse to normal voltage |
|---|---|---|---|---|---|
| | | Range | Weighted average | | |
| 66 | 54 | 4–6 | 5 | 750 | 13.9 |
| 88 | 72 | 5–7 | 6 | 890 | 12.4 |
| 110 | 90 | 6–9 | 7 | 1020 | 11.3 |
| 132 | 108 | 9–12 | 10 | 1410 | 13.1 |
| 154 | 126 | 10–12 | 10 | 1410 | 11.2 |
| 187 | 153 | 10–12 | 10 | 1410 | 9.2 |
| 220 | 180 | 12–16 | 13 | 1780 | 9.9 |

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6. *Effect of Transient Voltages on Dielectrics*, F. W. Peek, TRANS. A. I. E. E., Vol. 34, 1915, p. 1857.

is in the neighborhood of 10 to 14 times the crest value of the normal line to neutral voltage. This, together with the results of the klydonograph study, would indicate that the impulse flashover values given in Fig. 1 are fair values to use for the type of impulse which causes flashover on actual systems.

According to Mr. F. W. Peek's investigations, we may take the maximum potential gradient which may be induced on a transmission line by lightning as approximately 100 kv. per ft. of height of conductor. Actually, there have been measured by surge-voltage recorder, potentials which indicate gradients as high as 40 kv. per ft. of height. The readings obtained are subject to the fact that there is no assurance that the surge voltage recorders were located at the point of highest potential. The potentials are naturally limited by the insulator flashover, and such flashover potentials would require gradients in some cases as high as 60 kv. per ft. of height.

Assuming that the maximum potential gradient of 100 kv. per ft. of height can be obtained, and assuming further, that the flashover values given in Fig. 1 are substantially correct, then we have a means of determining whether or not a particular line will be subjected to flashover.

Mr. Peek, in his laboratory investigations, has determined fairly well the effectiveness of overhead ground wires. The protection afforded by the overhead ground wire depends on the distance of the ground wire from the conductors, on the height of the conductors above ground, and on the size of the ground wire and conductors. Generally speaking, however, any one of these factors may be varied within the range of practise without affecting the protective ratio to any great extent. The resistance of the connection to ground also has considerable influence on the protection.

Tables III, IV, V, and VI give comparative protective ratios for various average arrangements of practical transmission lines, assuming ground connections of low resistance. These values have been worked out by Messrs. Peek, Lloyd, and Clem and are based on calculation and tests on laboratory models. It is believed that they are fair values to use, although it is difficult to verify them definitely on actual transmission lines, except by a comparison of operating experience with and without ground wires.[3]

The values in Tables III to VI are given with considerable apparent accuracy, merely for the purpose of bringing out the difference between the various arrangements. However, in using values from the tables for calculations, they should be considered quite approximate.

The tables show ratios considerably greater than can be obtained by calculation with the classical formulas. Mr. C. A. Woodrow has offered an explanation of this as follows:

The potential gradient at the surface of the conductors and ground wire under lightning conditions, greatly exceeds the rupturing potential gradient of air. The air breaks down, forming corona, thus in effect enlarging the diameter of the conductors and ground wire. This, in turn, increases the capacitance between conductors and ground wire and correspondingly decreases the induced voltage on the conductors.

In placing ground wires it is desirable to adhere to the following general rules.

TABLE III
EFFECT OF GROUND WIRES ON EXCESS VOLTAGE, CONDUCTORS HORIZONTALLY ARRANGED

| Arrangement | Protective ratio | | Per cent decrease in excess voltage |
|---|---|---|---|
| .<br>o o o<br>1 2 3 | (1) | 0.45 | 55 |
| | (2) | 0.45 | 55 |
| | (3) | 0.52 | 48 |
| . .<br>o o o | (1) | 0.37 | 63 |
| | (2) | 0.32 | 68 |
| | (3) | 0.37 | 63 |
| .<br>o o o | (1) | 0.50 | 50 |
| | (2) | 0.44 | 56 |
| | (3) | 0.50 | 50 |
| . . .<br>o o o | (1) | 0.30 | 70 |
| | (2) | 0.27 | 73 |
| | (3) | 0.30 | 70 |
| .<br>. o o o . | (1) | 0.32 | 68 |
| | (2) | 0.28 | 72 |
| | (3) | 0.32 | 68 |
| . o o o .<br>. | (1) | 0.34 | 66 |
| | (2) | 0.31 | 69 |
| | (3) | 0.34 | 66 |

o Indicates conductor
. Indicates ground wire

$$\text{Protective Ratio} = \frac{\text{Voltage with ground wire}}{\text{Voltage without ground wire}}$$

TABLE IV
EFFECT OF GROUND WIRES ON EXCESS VOLTAGE CONDUCTORS VERTICALLY ARRANGED

| Arrangement | Protective ratio | | Per cent decrease in excess voltage |
|---|---|---|---|
| .<br>o o<br>o o<br>o o | (1) | 0.42 | 58 |
| | (2) | 0.52 | 48 |
| | (3) | 0.62 | 38 |
| . .<br>o o<br>o o<br>o o | (1) | 0.33 | 67 |
| | (2) | 0.39 | 61 |
| | (3) | 0.48 | 52 |
| .<br>o o<br>o o<br>o o | (1) | 0.40 | 60 |
| | (2) | 0.45 | 55 |
| | (3) | 0.42 | 58 |
| .<br>.<br>o o<br>o . o<br>o o | (1) | 0.46 | 64 |
| | (2) | 0.38 | 62 |
| | (3) | 0.44 | 56 |
| . . .<br>o o<br>o o<br>o o | (1) | 0.28 | 72 |
| | (2) | 0.33 | 67 |
| | (3) | 0.41 | 59 |

o Indicates conductor
. Indicates ground wire

$$\text{Protective ratio} = \frac{\text{Voltage with ground wire}}{\text{Voltage without ground wire}}$$

TABLE V
EFFECT OF GROUND WIRES ON EXCESS VOLTAGE
CONDUCTORS HORIZONTALLY ARRANGED

| Arrangement | Protective ratio | Per cent decrease in excess voltage |
|---|---|---|
| . .<br>o o o o o o<br>1 2 3 4 5 6 | (1) 0.50 | 50 |
| | (2) 0.42 | 58 |
| | (3) 0.36 | 64 |
| . .<br>o o o o o o | (1) 0.43 | 57 |
| | (2) 0.41 | 59 |
| | (3) 0.42 | 58 |
| . . .<br>o o o o o o | (1) 0.39 | 61 |
| | (2) 0.35 | 65 |
| | (3) 0.28 | 72 |
| . . . .<br>o o o o o o | (1) 0.33 | 67 |
| | (2) 0.28 | 72 |
| | (3) 0.26 | 74 |
| . . . . .<br>o o o o o o | (1) 0.31 | 69 |
| | (2) 0.26 | 74 |
| | (3) 0.23 | 77 |

o Indicates conductors
. Indicates ground wire
Conductors 6, 5, 4 have same protective ratio as 1, 2, 3 respectively

$$\text{Protective Ratio} = \frac{\text{Voltage with ground wire}}{\text{Voltage without ground wire}}$$

TABLE VI
EFFECT OF GROUND WIRE ON EXCESS VOLTAGE
CONDUCTORS TRIANGULARLY ARRANGED

| Arrangement | Protective ratio | Per cent decrease in excess voltage |
|---|---|---|
| .<br>o 2 o5<br>o o o o<br>1 3 4 6 | (1) 0.53 | 47 |
| | (2) 0.47 | 53 |
| | (3) 0.51 | 49 |
| .<br>o . o<br>o o o o | (1) 0.42 | 58 |
| | (2) 0.36 | 64 |
| | (3) 0.38 | 62 |
| . .<br>o o<br>o o o o<br>. | (1) 0.45 | 55 |
| | (2) 0.42 | 58 |
| | (3) 0.42 | 58 |
| .<br>o o<br>. o o o o . | (1) 0.31 | 69 |
| | (2) 0.32 | 68 |
| | (3) 0.30 | 70 |

o Indicates conductors
. Indicates ground wire
Conductors 6, 5, 4 have same protective ratio as 1, 2, 3 respectively

$$\text{Protective Ratio} = \frac{\text{Voltage with ground wire}}{\text{Voltage without ground wire}}$$

1. The wires should be connected to each tower or connected to ground at each wooden pole.

2. The resistance of the tower footing or the pole ground must be low in order to give the maximum protection.

3. The ground wire should preferably be of the same material as the conductor, or other high conductivity material. This will prevent rusting and will have an appreciable effect in reducing the impedance of the system to line-to-ground short circuits. It will also reduce telephone interference by shunting a good portion of the short-circuit current away from the ground.

4. The ground wires should terminate at the station structure rather than at the first or second tower out on the line. This assures that the last span or two near the station, will be protected, and that there will be no abrupt change in the surge impedance of the line at the terminal of the ground wire. Such a change in surge impedance tends to cause an upward reflection in the voltage of a wave arriving on the transmission line.

The conductivity of the ground wire apparently has very little effect on its protective value, as the protective value depends on the reduction in charge on the line conductors and the increase in capacitance of the conductors to ground, and this is independent of the material of the ground wire. High conductivity is very beneficial, however, in relaying and in preventing telephone interference as previously mentioned.

Now, if we know the potential gradients which may be due to lightning, the flashover value of the line insulators and the protection afforded by overhead ground wires, we are in a good position to determine what must be done to render the transmission line fairly safe from insulator flashover.

In Table VII are given the actual average heights of the lowest conductor at the tower for the various standard system voltages as disclosed mainly from a study of the data given in the *Electrical World Supplement* of January 3, 1925. In this table are given also the potentials which may be obtained with a gradient of 100 kv. per ft. Comparing these potentials with the flashover value of the line insulators in Table II, we see that it is possible to have insulator flashover under the assumed conditions for every system voltage.

TABLE VII
HEIGHT OF ACTUAL LINES AND INSULATION REQUIRED TO PREVENT FLASHOVER

| System voltage | Average height of lowest conductor at tower feet | Possible lightning potential 100 kv. per ft. | Potential with two ground wires conductors horizontally arranged | No. of ins. disks required to prevent flashover | Flashover of insulator disks kv. |
|---|---|---|---|---|---|
| 66 | 35 | 3500 | 1290 | 9 | 1280 |
| 88 | 39 | 3900 | 1440 | 10 | 1410 |
| 110 | 47 | 4700 | 1740 | 13 | 1780 |
| 132 | 47 | 4700 | 1740 | 13 | 1780 |
| 154 | 50 | 5000 | 1850 | 14 | 1900 |
| 187 | 50 | 5000 | 1850 | 14 | 1900 |
| 220 | 56 | 5600 | 2070 | 16 | 2140 |

Assuming the average heights shown in Table VII and a horizontal arrangement of conductors with two overhead ground wires placed above and between the conductors, the potential induced on the conductors will be reduced to approximately 37 per cent of the value without ground wires; *i. e.*, to the values shown in the fourth column of Table VII. Now, in order to prevent flashover, it will be necessary to use the number of insulator disks shown in the fifth column of the table. The insulation required to produce immunity in this manner is considerably higher than the present standard.

Of course, if the conductors were arranged vertically, the situation would be still less favorable. For example, let us assume the heights for top, middle, and bottom conductor shown in Table VIII. Then the potentials without ground wire at 100 kv. per ft. of height would be as given in the third column of the table. Now assume that there are two ground wires placed vertically above the two circuits of a double circuit arrangement. Using the protective ratio given in Table IV, we should arrive at the potentials given in the fourth column of Table VIII. In order to prevent flashover in this case, it would be necessary to use the number of insulator disks shown in the fifth column of this table.

Mr. Peek has found that grading rings, properly proportioned and properly located, will increase the flashover value of a string of insulators, (especially strings containing 10 disks and over), approximately 10 to 15 per cent and this effect may be taken advantage of in reducing the number of insulator disks or in increased factor of safety.

TABLE VIII
VERTICAL ARRANGEMENT OF CONDUCTORS, POTENTIAL INDUCED, AND INSULATION NECESSARY TO PREVENT FLASHOVER

| Conductor | Conductor Height ft. | Potential without ground wires 100 kv. per ft. | Potential with two ground wires 100 kv. per ft. | No. of insulator disks required to prevent flashover | Impulse flashover kv. |
|---|---|---|---|---|---|
| Top....... | 75 | 7500 | 2480 | 19 | 2500 |
| Middle.... | 60 | 6000 | 2340 | 18 | 2380 |
| Bottom.... | 45 | 4500 | 2160 | 16 | 2140 |

It is apparent from this study that the potential induced on a transmission line is independent of the operating voltage, except in so far as the height of the conductors and the number of insulator disks is affected by the operating voltage. In selecting the number of insulator disks, it may not be necessary to consider the extreme potential gradient of 100 kv. per ft. of height. A gradient of 75 kv. per ft. will probably be sufficient to cover the great majority of cases, and a line insulated for this gradient would no doubt be immune from flashover except in rare instances.

Now, what is the situation as regards apparatus insulation, especially transformer insulation. The insulation of power transformers is designed to withstand a certain 60 cycle high potential test, this high potential test being, for fully insulated transformers, two times the line-to-line voltage. The test is applied from high tension winding to low tension winding and ground. In the so-called reduced insulation transformers, which are built for operation with solidly and permanently grounded neutral, an induced voltage test of 2.73 times the leg voltage is given to the transformer windings.

Naturally the designers build into the transformer a factor of safety over the Institute test. Such a factor of safety has been worked out by experience and has proved ample to meet the various switching and arcing ground surges to which transformers are subjected.

With the range of line insulation shown in Table II it has been possible for transformers to be subjected to lightning voltages from 10 to 14 times the normal operating voltage with the average line insulation and more than that with the maximum insulation shown in the table. Such voltages, of course, are subjected to the modification caused by lightning arresters, the capacitance to ground of steel work used in supporting bus structures, etc. Also on any system probably only a fraction of the lightning discharges takes place near stations. However, it is reasonable to suppose that transformers have been subjected many times to ten times normal voltage. Transformers have operated under these conditions with remarkable success, the failures due to all causes including lightning, being only a fraction of one per cent per year.

It is reasonable to conclude that fully insulated transformers with present standards of insulation will operate successfully on systems with present average insulation. If such line insulation is increased, as now seems to be the tendency, then the transformer insulation must be correspondingly increased, unless the present standard line insulation is retained for a reasonable distance adjacent to the station, say, one-half to one mile.

If fully insulated transformers are on a par or slightly stronger than the present average line insulation, then it is apparent that reduced insulation transformers are too weak, as their strength is only about 80 per cent of that of fully insulated transformers. Reduced insulation transformers for this reason have no place on systems subjected to much lightning, unless the adjacent line insulation is correspondingly reduced.

In order to protect transformers now in operation and future transformers with standard insulation, it is recommended that the line insulation adjacent to stations be not increased beyond the values given in Table IX for at least one-half mile from the station.

TABLE IX
RECOMMENDED LINE INSULATION

| System voltage kv. | Recommended 60-cycle arc-over of line insulators—kv. effective | Corresponding number of 10-in. disks spaced 5¾ inches |
|---|---|---|
| 66 | 255 | 4 |
| 88 | 355 | 6 |
| 110 | 400 | 7 |
| 132 | 445 | 8 |
| 154 | 540 | 10 |
| 187 | 620 | 12 |
| 220 | 700 | 14 |

Beyond that point there is no objection to increasing the line insulation to any value required to give good operation. Such a practise on the part of the operating companies will give the manufacturers a definite standard with which to compare their apparatus design.

If for any reason it is desired to increase the line insulation adjacent to the station, then the apparatus insulation should be increased correspondingly.

In cases where it is thought desirable to increase the line insulation and it is feared that maintaining normal insulation near the station will increase the number of flashovers, this may be compensated for by placing additional ground wires over this portion of the line, thereby reducing the potential induced by adjacent cloud discharges to correspond to the reduced number of insulator disks. Such ground wires should extend to the stations and, in some cases, over the stations, in order to insure that the station apparatus secure the full benefit of the ground wires.

The impulse flashover value of standard General Electric bushings is, in general, on a par with the line insulation strength. If a wave gets by the line insulation without flashing over, and reflects to a higher magnitude on reaching the transformer winding, the bushing may flash over and thus offer a means of relieving the transformer insulation. The character and type of waves are so varied that neither the line insulation nor the bushing may be depended upon to protect the transformer in all cases. All that can be said is that if their flashover value is not too high with respect to the transformer strength, there is a pretty good chance that they will flash over and relieve the transformer of at least the greater part of the energy of the wave.

Sometimes power companies call for an especially tall bushing, where the transformer is operated in a district subject to smoke, dust, salt spray, etc. These foreign materials together with moisture reduce the flashover voltage of the bushing. In these cases the long bushing may be used to improve the creepage situation, and the impulse flashover may be kept down to correspond with the transformer insulation by a suitable auxiliary ring or horn gap. Such increased length bushings may afford only temporary relief from creepage as in time dirt will accumulate and their flashover voltage may be reduced to a value comparable to that of a standard bushing. Frequent cleaning may be necessary in either case.

In order to provide a further assurance of successful operation and take care of surges of all kinds, it is necessary to by-pass the incoming surge. The cheapest and most effective present form of such a by-pass, is a lightning arrester.

Mr. K. B. McEachron found that by means of the cathode ray oscillograph, lightning arresters of the oxide film type will hold down the voltage to approximately 1 to 1.8 kv. per cell, depending on the steepness of the wave front.[7] The value of 1.8 kv. per cell corresponds to the standard Pittsfield wave which we have been discussing, and probably also to the steepest waves likely to be encountered in service. Such an arrester, if placed directly at the transformer terminals or as near to the transformer terminals as physically possible, will prevent appreciable reflection and hold down the voltage to a value that is safe under all conditions.

In selecting arresters, the number of cells for a given system is varied, depending on the dynamic overvoltage which may be expected when the load is dropped, in which case the over-speeding of the prime mover and the regulation of the generator may cause a considerable rise in voltage. If this dynamic voltage can be kept to a low value by distribution of load and relaying of the system, or if it naturally comes to a low value owing to the characteristics of generator and prime mover, then a fewer number of cells may be used and still better protection may be secured. This is a very important point and one that should be taken into consideration in all cases.

To summarize: We have shown that it is possible to increase the safety of transmission lines and apparatus from lightning disturbances by adhering to the following principles:

a. Construct the transmission line so that the conductors are as near to the ground as the necessary clearances will permit, and preferably build the line with the conductors horizontally arranged.

b. Install one or two overhead ground wires in accordance with the design of the tower and the requirements for reduction in potential imposed by the height of the conductors.

c. Use sufficient insulation on the line to prevent flashover with the maximum potential gradient that may be obtained with the number of ground wires used.

d. Maintain recommended insulation (Table IX) for one-half a mile or so from the station in order to protect station apparatus. Over this section, additional ground wires extending to the station may be used in order to place this section on a par with the over insulated section as far as flashovers are concerned.

e. Install lightning arresters immediately adjacent to the transformers so as to prevent reflection and hold down the potential to a comparativly low value.

## Discussion

For discussion of this paper see page 1009.

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[7] "Protection of Station Equipment on High-Voltage Transmission Lines," K. B. McEachron, *G. E. Review*, May 1928.

# Rationalization of Transmission System Insulation Strength

BY PHILIP SPORN*

Member, A. I. E. E.

*Synopsis.—Experience on high-voltage transmission lines has shown numerous failures of apparatus which have indicated a decided lack of coordination of the insulation strengths of the various parts of the transmission system. Apparatus offered by manufacturers for a given service shows wide variations in insulation values. Again the flashover and the breakdown values are not at present sufficiently standardized to be comparable among manufacturers of the same piece of apparatus. The standard tests on different types of apparatus are not properly correlated.*

*This paper, besides discussing the above situation, points out the causes for the present status, and indicates the benefits to be derived by grading the insulation on the entire system. Predetermining the point of electrical breakdown on the system in the case of high voltage surges leads most logically to grading the insulation. This grading should result in fewer major service interruptions, with a localization of trouble on a link of the system where repairs can be made easily and inexpensively.*

*The paper points out that additional information is required on surge voltage breakdown of insulation to solve the problem completely but shows that with the present information available a start in grading can be made. The different links in the transmission chain are tabulated according to their relative importance and with this as a starting point, the entire grading scheme is developed to the point of showing relative 60 cycle insulation strength required of the different apparatus used on a transmission system.*

*It is shown: 1, that transmission systems in general, at the present time, are designed without proper consideration from the standpoint of surge voltages which may be imposed upon them; 2, that the grading scheme proposed is possible, although requiring additional operating data and data from the manufacturers to be fully effective; 3, that grading should result in less costly designs and installations; 4, that the net effect will be better performance of the transmission system in service.*

* * * * *

## I. INTRODUCTION

THE idea that it ought to be possible to place insulation strength of the various portions of a transmission system on a rational basis, instead of the present more or less haphazard basis, is perhaps not new, and has undoubtedly occurred to many. It has not occurred to a large enough group, however, or not with potency enough to bring about any action. To the writer the idea first occurred three or four years ago, because the problem was forcefully called to his attention by operating experience. In one particular case, a 23,000-volt belt was placed around a city. The line was well over-insulated; in fact, it was equipped with 45,000-volt pin insulators of an especially liberal design. The following year oil circuit breakers were placed on the loop for sectionalizing purposes. In the first summer of their operation an epidemic of broken bushings on oil circuit breakers, current, and potential transformers broke out. This led to an investigation of the relative insulation values and strengths of the line insulators and of the bushings of the oil circuit breakers and of the current and potential transformers.

In another instance, with a system voltage of 23,000 volts, standard 37,000-volt oil circuit breakers were employed, but the potential transformers and the high voltage metering equipment used on the system was standard 25,000-volt equipment. Here it was found that the trouble was concentrated on the metering equipment and potential transformers, whereas the oil circuit breaker bushings were comparatively free from trouble. On still another system, the transformers employed were not standard transformers but were transformers designed and tested for three times normal line potential instead of the standard double line potential. The insulators, however, employed for insulating the bus and the disconnecting switches, were standard pin type insulators of the approximate rating of the line. Here practically no trouble was experienced with the transformers or their bushings, but a considerable amount of trouble was experienced with the bus insulators due to flashover and breakdown.

All this experience naturally led to the idea that the probable cause of trouble was that a certain part of the system was insulated without regard to the insulation strength of the component parts of the system, and that it was quite possible that the particular part which was heavily insulated was not the right one. This suggested that it ought to be possible to place the entire problem of insulating the various parts of a transmission system on some rational basis, strengthening or weakening either one part or another in accordance with a preconceived and planned system of grading.

Experience gathered since then has shown the desirability of working out some such idea A great deal of this experience has been on a 132,000-volt system. All of it, however, tended to show definitely that some such plan ought to be evolved and that a considerable saving in labor of design and a considerable improvement in the quality of service of the transmission system could be secured if such an arrangement were adopted.

The present paper is to be regarded not as a complete solution but rather an attempt at the beginning of this problem.

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*Presented at the Northeastern District No. 1 Meeting of the A. I. E. E., New Haven, Conn., May 9-12, 1928.*

## II. PRESENT STATUS IN REGARD TO TRANSMISSION INSULATION

Perhaps no better illustration of the present chaotic condition with regard to insulation strength and ratings can be obtained than by an excursion to catalogs of the various manufacturers. Consider the status among the insulator and bushing manufacturers. In Tables I, II, and III are shown the flashover values of 132-kv., 70-kv., and 45-kv. post type insulators of various manufacturers. The flashovers are in many cases given in the catalog. In other cases they could be obtained only as a sort of special favor. From a surface inspection it will be seen that variations in flashover of from 25 per cent up to 33 per cent are not at all unusual. Yet not all is seen on the surface. Some of the values listed are sphere-gap determinations, others are needle-gap determinations, and still others are given as test values and not as flashover values at all. The manufacturer did not hesitate to give the apparatus a voltage rating; acting on the assumption, presumably, that he was perfectly competent to perform such a function, and that it was not at all necessary for the user of the apparatus to know the basis on which the rating was arrived at. That this indicates a looseness in arriving at ratings is apparent.

TABLE I

132-KV. POST TYPE INSULATORS

| Manufacturers | A | B | C | D | E |
|---|---|---|---|---|---|
| Rating (kv.) | * | 165 | 200 | 140 | 132 |
| Dry F. O. (kv.) | 355 | 390 | 398 | 448 | 390 |
| Wet F. O. (kv.) | 285 | 315 | 320 | 370 | 287 |
| Shells per unit | 3 | 3 | 4 | 1 | 1 |
| Units per post | 3 | 3 | 3 | 8 | 8 |
| Diameter (in.) | 17 | 17 | 17 | 14 | 11-1/8 |

*Manufacturer does not rate

TABLE II

70-KV. POST TYPE INSULATORS

| Manufacturers | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| Rating (kv.) | 70 | 70 | 72 | 66 | 73 | 73 | 66 | 70 | 70 |
| Dry F. O. (kv.) | 180 | 192 | 215 | 240 | 200 | 195 | 215 | 215 | 218 |
| Wet F. O. (kv.) | .. | 137 | 145 | 148 | 150 | 145 | 135 | 150 | 150 |
| Leakage dist. (in.) | 38½ | 39 | 37½ | .. | 50½ | 50½ | 35 | 40½ | .. |
| Shells per unit | .. | 4 | 4 | .. | .. | .. | 3 | 4 | 4 |
| Units per post | 1 | 1 | 1 | 4 | 1 | 1 | 1 | 1 | 1 |
| Diameter (in.) | 15 | 14 | 15 | 11–1/8 | 16 | 16 | 13½ | 14 | 16 |

TABLE III

45-KV. POST TYPE INSULATORS

| Manufacturers | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Rating (kv.) | 45 | 45 | 45 | 45 | 45 | 50 | 44 | 40 | 50 | 45 | 45 |
| Dry F. O. (kv.) | 170 | .. | 143 | 140 | 130 | 135 | 198 | 145 | 190 | 131 | 140 |
| Wet F. O. (kv.) | 95 | .. | 95 | 90 | 95 | 100 | 115 | 110 | 121 | 81 | .. |
| Leakage dist. (in.) | 21¼ | 25 | 17½ | 18½ | 22½ | 25 | .. | .. | .. | .. | 25 |
| Shells per unit | 2 | 3 | 3 | 2 | 3 | 3 | 1 | 2 | 3 | 3 | 3 |
| Units per post | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 1 | 1 | 1 | 1 |
| Diameter (in.) | 10½ | 11 | 10¼ | 11 | 9½ | 10½ | 11–1/8 | 12 | 13½ | .. | 10½ |

No better condition exists in the bushing situation, and Table IV shows that up fully. For example, between manufacturer A and manufacturer C on 132-kv. bushings there is more than a 56 per cent difference in wet flashover value, when expressed in terms of the lower of the two values. Obviously there has been no scientific yardstick employed in the determination of ratings of their bushings by the various manufacturers, or else there would not be the discrepancy and variation shown. Tables like this could be compiled to show similar and worse conditions among other groups of insulators; but it is believed that more than enough has been shown to indicate the general fact that the present system of ratings is confusing, chaotic, and, in fact, very often dangerous.

TABLE IV

HIGH-VOLTAGE PORCELAIN BUSHINGS

| Manufacturer dry or wet voltage rating | A | | B | | C | | D | |
|---|---|---|---|---|---|---|---|---|
| | Dry | Wet | Dry | Wet | Dry | Wet | Dry | Wet |
| 33-kv. | 120 | 95 | 155 | 120 | 140 | 112 | 115 | 70 |
| 44-kv. | 160 | 130 | 180 | 150 | 180 | 145 | 140 | 115 |
| 66-kv. | 190 | 150 | 240 | 200 | 215 | 180 | 170 | 135 |
| 132-kv. | 300 | 200 | 375 | 280 | 385 | 330 | .. | .. |

The situation among the apparatus manufacturers may not be quite so bad, but certainly it cannot be called good or orderly. At the present time we have a group of more or less standard voltages on which the design classes are based; but the various groupings of classes are not the same for different classes of apparatus. Further, among these various groupings there are undoubtedly manufacturing classes and these classes may, and probably do, differ from the usage voltage standards. Again, various parts of specific designs are often not correlated and under many existing conditions, cannot be. For example, there are many switch manufacturers who do not make their bushings; there are many transformer manufacturers who do not make them. It is quite obvious that as long as the bushing manufacturer himself is held to no standards in the rating of his bushings, some of that same confusion is bound to creep into the equipment of which these bushings form a part. This, of course, is not meant to imply that such a situation cannot occur and has not occurred, where all the various parts of a piece of apparatus have been made by a single manufacturer. A number of examples came to hand recently in a test of some distribution transformers, on equipment that has been built now for 30 or 40 years, and for such a standard voltage as 2300 volts, it was found in some cases there was 50 per cent variation in the impulse flashover value of the bushings of transformers of various manufacturers. Obviously one cannot conclude from such experience or data that there was ever very much knowledge on the part of some of the designers with regard to the impulse flashover value of the bushing, or that an attempt had ever been made to correlate any such knowledge.

Nor is there any better agreement among the various state regulatory bodies who formulate state rules and regulations, nor between them and the Safety Code.

Each one of these has attempted to lay down a set of minimum standards but there certainly is no unanimity of opinion or of rule as to what such a minimum should be. A glance at Curves 7 and 8 of Fig. 1 will fully bring this out.

One would think that the operating companies, and those designing and constructing for them, would at least have seen the necessity for bringing some order into this whole problem, but it does not happen to be the case. The more one talks with the manufacturers, the more one realizes the predicament in which they find themselves, in attempting to carry out the various ideas of the various organizations with regard to the relative values of insulations of component parts of apparatus. If one examines different practises one finds one system particularly bent on over-insulating its lines, another system practising over-insulating its transformers and having its bushings of normal strength, and still another following reverse practise of having extra heavy bushings and normal insulation on windings. These conditions will be found to exist in the moderate voltages; and in the higher voltages they are sometimes even worse.

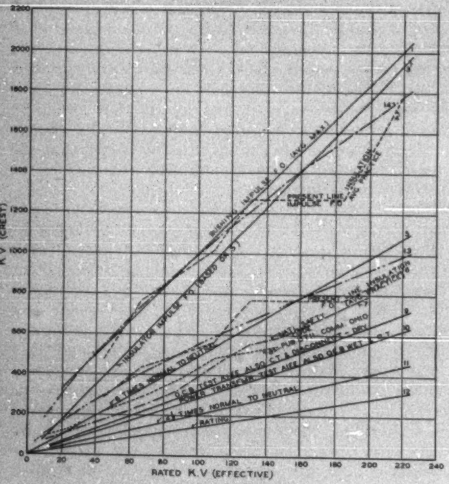

FIG. 1—TRANSMISSION SYSTEM INSULATION STRENGTHS CONDITIONS IN 1927-1928

1 Bushing impulse voltage F. O. (general average)
3 Line insulator impulse F. O. (based on 6 × normal 60 ~ F. O.)
4 Line insulator impulse F. O. (based on present avg. insulation)
5 6 times normal—line to neutral 60 ~ voltage
6 Line insulator 60 ~ F. O. (present avg. insulation)
7 Min. allowable line insulator 60 ~ F. O.—National Safety Code
8 Min. allowable line insulator 60 ~ F. O.—Public Utility Comm. of Ohio
9 60 ~ dielectric test—Oil C. Bs.—C. Ts disconnects—A. I. E. E. dry
10 60 ~ dielectric test power transfs.—P. Ts dry—O. C B. wet—A.I.E.E.
11 2½ times normal line to neutral—60 ~
12 Apparatus rating—60 ~
13 Line insulation (approx. present avg.—60 ~ F. O.)
14 Line insulation (approx. present avg. impulse F. O.)

The effect of this entire situation is to leave one with a general impression that the whole matter is so confused that it would be hopeless to try to change it and bring order into it. In fact, the suggestion has been made at times that in view of the fact that things are working so well on the whole, it is questionable whether a change ought to be attempted; but with this view the writer finds it very difficult to agree. A glance at Fig. 1 makes it all the more difficult.

In Fig. 1, Curve 12 indicates the crest value of various voltage ratings. Curve 11 shows, for various ratings, the crest value of 2½ times normal from line to neutral. This is the maximum value of potential due to an arcing ground on a grounded neutral system where the system is grounded through a resistor below the critical value.[1] In Curve 10 are shown the standard A. I. E. E. test on power transformers, the wet test on oil circuit breakers, and also the dry test on potential transformers. Curve 9 shows the dry A. I. E. E. test on oil circuit breakers and also test on current transformers and disconnects. Curves 8 and 7 show the minimum insulation strengths required by the Public Utility Commission of Ohio, Administrative Order No. 72, and by the National Safety Code respectively. Curve 6 shows the average practise at the present time on line insulation values.[2] The irregularities in practise disclosed by this curve are unusually interesting. Curve 5 is a line drawn through points representing six times the normal to neutral potential. It has been shown[1] that the maximum potential possible due to an arcing ground on an ungrounded neutral system is approximately six times normal to neutral and Curve 5 is introduced here to show the relationship between it and the curve of present practise.

Curve 4 is a translation of curve 6 in terms of impulse flashover utilizing an impulse ratio of 1.8. Curve 3 is curve No. 5 translated in terms of impulse voltage utilizing the same impulse ratio of 1.8; and curve 1 shows the impulse flashover of bushings for various operating voltages. The impulse breakdown of transformers is not given in curve form as the data on this subject are at present far from complete, particularly on transformers that are now in service and that were designed before the importance that is now being attached to the characteristics, as regards impulse strengths, was given much weight. It is known definitely, however, that there are many cases where impulse breakdown voltage is below bushing flashover value; that is, many cases are known where transformers have failed internally without having any flashovers across their bushings. In other words, the bushings failed to give them the protection that they would be expected to give if their flashovers were below the failure point of the transformer itself. It is hard to study the various curves and not come to the conclusion that there is a better arrangement than exists at the present time.

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[1] See "Arcing Grounds" by G. E. Clem, *General Electric Review*, Vol. 31—also "Gounding the Neutral through Resistance" by W. W. Lewis, *General Electric Review*, Vol. 31.

[2] *Electrical World*, Supplement, January 3, 1925.

### III. Analysis of the Present Situation

An analysis of just how the present situation came about may be of benefit. The present status is the result of a large number of factors. In the first place the art and the industry have grown tremendously, and at a rate that hardly left time for detailed analysis. This is particularly true with regard to the transmission problem. In this country until 10 or 12 years ago, with the exception of a few isolated cases, the transmission problem was one of no great consequence to the average power company. Most of the territories relied on locally placed plants for their important loads; and what transmission was done was for comparatively unimportant load. Further, the amount of capacity involved and general spread of the system were so small that many of the problems with which we are confronted today were not known, or at least existed only in a much milder form. The development during the past decade of networks with large concentrations of power has taken place under pressure of time. Consequently, it is not at all surprising to find ideas that were developed in one territory were taken over, very often bodily, and applied without proper evaluation, in another territory where an entirely different set of conditions existed, and where the same practise could not be followed with impunity. That undoubtedly has been one cause.

Another cause has been the lack of knowledge with regard to the fundamental phenomena that are causing trouble. The present ideas with regard to lightning and surge phenomena had been known for some time but it had never been possible, except with great difficulty, to secure actual data. Lack of facilities both in money and men to carry out any investigations, except by the isolated few, has resulted in a condition where only the most meager data were available on insulation values of insulators and structures, on the causes of flashover, and on the values to be employed in insulation. There has not yet been published or disclosed, at least in this country, an oscillogram of an actual lightning wave. With lack of actual data, therefore, to prove definitely the nature of lightning and of surges, ample room has been left for theorization, and so a number of theories has arisen and flourished, and many installations and designs have been made on the basis of these with, very often, sad results under operating conditions.

Again, as already stated, some of the old high-voltage systems were isolated neutral systems and the insulation values developed for them were based on isolated system operation. Today practically all of the systems are operated with grounded neutral yet no differentiation has been made in the insulation strengths of the two systems. Perhaps none should be made above a certain voltage, if the line insulation is to be chosen primarily with a view of its lightning flashover, but the point is, that if the line is to be designed from a lightning standpoint, that is, if lightning is to be the predominating factor that will determine the line insulation, that ought to be definitely established and the problem will be so much simpler.

Another phase of the lack of knowledge of the fundamental phenomena causing trouble has been the almost complete absence of data on lightning and switching surges and the trouble that they cause. This has been partially remedied in the last few years by the invention of the klydonograph, but the total information available, which has been properly analyzed, is not even half sufficient.

The result of this lack of data and information has been that even where intelligent design was attempted, the actual execution of such design was not at all easy. This, in turn, has had one direct result—trouble, and generally unexpected trouble. Sometimes it takes the form of extensive line flashover, sometimes of extensive line breakage or conductor burning; sometimes it appears as apparatus failure as in transformers, disconnecting switches, or oil switches. But the trouble will always show up ultimately, and when it does occur there is generally a stirring to find out the cause and remedy.

Typical cases of the kind mentioned are undoubtedly known, but perhaps specific cases will bring home the point more clearly. In one case, a 1500-kv-a., three-phase, 132,000-volt transformer stepping down to 33,000 volts failed through a lightning breakdown on the 132,000-volts, volt side. The high tension coils of one of the phases were completely destroyed. This particular transformer received a factory test according to the standard A. I. E. E. Rules, that is, 265 kv. to ground for one minute and also the standard double induced-voltage factory test. This transformer had a lightning arrester installed on the high tension side. In another case a similar transformer located in an entirely different type of country, failed in one phase of the high voltage windings. The breakdown caused a burning of two widely separate parts of the winding. The arc jumped from the winding to ground in one place and from the voltage ratio adjuster to ground in another. This transformer had no lightning arrester installed on the high side. In both of these transformers no damage was done to the bushings. Obviously, therefore, the bushings did not act as any protective gaps for the transformers. Still another case came under observation on a 30,000-kv-a. auto-transformer bank stepping down from 132,000 to 88,000 volts. Four flashovers occurred between the high-voltage and low-voltage bushings within a short time, doing very little apparent damage to the transformer itself, however, but resulting in each case in a very brief service interruption. On the fourth flashover the corrugations on the low-voltage bushings were broken and the bushing cracked so that it leaked oil and had to be replaced. At the time of the last flashover on this transformer, a klydonograph was on it and the readings showed a potential difference of approximately 850-kv. crest between the two bushings where flashover occurred, and a potential difference of approximately 640-kv. between the corresponding parts of another phase where no flashover occurred. Here was an instance of four cases of trouble without any appreciable visible damage to the transformer. Apparently the bushings acted as excellent protective gaps to the winding.

Instances of trouble on pedestal-type insulators will be cited. In one case a switch insulator on an air-break switch arced over when the charging current of 50 mi. of 132-kv. line was broken through the switch. The same experience was obtained some five months later when the switch was made to perform the same operation.

The history of the Philo-Canton line and the light this has thrown on line insulation practise has already been reported.[3] That this experience is not isolated experience is borne out by the fact that one company this year, after years of operation of a 110-kv. transmission line, has decided to increase the number of ground wires and the insulation on their line.

There are many other cases known which need not be cited. The main thing is, that if operating experience is only investigated far enough, it will be found that there are plenty of data to bear out the fact that there exists ample trouble due to improper insulation strength on our transmission systems, and that this trouble shows up in every phase of the transmission chain. There is bus trouble; there is bushing trouble; there is transformer trouble—for every link in the chain of the transmission system there will be found conditions where breakdowns occurred on that particular link and in many cases the breakdowns occurred on a number of links at the same time.

The difficulty of the situation which generally arises when such a case of trouble occurs is due to the fact that the average transmission system is not a laboratory. Experiments cannot be carried out and the engineer is not allowed, nor should he be allowed, to experiment too widely. The thing that is necessary is to reestablish service, and quickly. The remedy that is therefore applied is chosen from those that can be obtained quickly, and too often the permanency of the cure is in inverse ratio to the speed with which it can be obtained.

What is generally done in a case like that? The apparatus user appeals to the manufacturer, or to a group of manufacturers, for help in the solution of the problem. But it does not follow necessarily that the manufacturer is in a position to give any relief. Often the problem is beyond him, due to the lack of the fundamental data underlying the problem. A part of the blame for this, it is true, rests with the user of the equipment. In the past, equipment has been purchased with practically no attention to its characteristics until operating trouble focuses the attention of the user on those characteristics. The consequence of this has been that in many instances the manufacturer has adopted the attitude that it is a direct reflection on his manufacturing and engineering ability if any question is raised with regard to some of these points, so that today the user finds himself in a position of being unable to get information on characteristics when he asks for it, or to get any sort of guarantee with regard to performance under certain conditions. And yet, if design is to be handled intelligently and if troubles are to be anticipated, all these phases have to be looked into in advance, and that means having the data in advance.

## IV. PROPOSED INSULATION CHAIN

If what has been brought up till now has shown anything conclusively, it should be the fact that properly graded insulation values, rather than haphazard values, are vital and necessary under present conditions. The coming to the foreground of interconnection, with the continued expansion of the amounts of power that will be dependent upon transmission and transmission systems for their proper routing and distribution, combined with the higher standards of dependability, make it imperative that this problem, because of its vital importance to such continuity of service, be solved, and quickly.

The problem, which is one of interest to both the manufacturers and the users of electrical equipment involved in a transmission system, is, however, of greater importance to the users and it would appear logical that they should be the proponents of such a movement. For after all there is a large group of manufacturers making equipment involved in the transmission chain, and each individual manufacturer cannot look out for more than his own particular portion. Often, indeed, different departments of a particular manufacturing group are interested only in their own particular parts of a piece of apparatus. The users of the apparatus, however, have to take care of the combined troubles of all of them, and they are therefore the greatest potential losers under a condition where the various portions are not properly correlated.

The writer believes that grading can be accomplished by a proper study and cooperative effort. It is not necessarily simple, but it most surely can be done. There is no doubt of its importance. But yet it has not been done so far.

Undoubtedly one of the causes that have blocked rationalization of insulation in the past has been the fact that the rating of apparatus has been by voltages and very often the voltages were differently divided on the different classes of apparatus. Further, the rating while probably conforming to A. I. E. E. tests had very little else as a basis for the establishment of the particular rating. It is conceded that the A. I. E. E. test is lacking in many respects since it leaves open to the manufacturer phases of design which have a material effect on its performance on the line. In many cases, as already pointed out, these data are not known even to the manufacturer. Again, one of the causes that has blocked rationalization has been hard economics. To illustrate, if a given 44,000-volt system had to contend in a certain district with conditions of service that were at least as hard on apparatus as a 73,000-volt system in some other district, it is difficult for the designer to bring himself to the point where he will specify 73,000-volt equipment if he is not to appear extravagant, particularly to his executive superiors. Yet in that case, what it is really necessary to specify is insulation strength and not voltage at all.

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[3] *Lightning and Other Experience with 132-Kv. Steel Tower Transmission Lines*, Sindeband and Sporn, A. I. E. E. TRANS., Vol. 45, 1926, p. 770.

All this can be overcome by dividing insulation into classes, each class to contain the whole series of links used in the transmission chain and the entire series properly graded. This will be elaborated upon further. The idea, however, is sound. Our experience with 132-kv. system has already been cited. We have had experience with 66,000-volt systems which, while not proving conclusively, indicates fairly well that there is a possibility of designing a system so as to be practically free from insulation troubles.

### V. Fundamentals of the Problem

Before considering the detailed analysis of the various insulation classes it might be well to consider the causes of flashover. An insulator will flash over to ground or to another member when the voltage to ground, or to the other member, is greater than the insulating value of the insulator plus the supporting structure from the live point to ground or of the insulator plus intervening space to the other member. Broadly, this covers also cases of puncture. These overvoltages may be of several types and of several sources of origin:

1. A straight overvoltage at the power frequency caused by a system running away, by the crossing of circuits of various potentials, or by some other unusual occurrence.

2. An overvoltage may appear due to arcing grounds. This voltage may have a frequency of the order of thousands of cycles. Except for the isolated neutral systems which are rare today it will, of course, not appear.

3. Overvoltages may take the form of impulse voltages and these, in turn, may be caused either by switching or by lightning.

It has already been shown (1) that where a system is grounded, even with a considerable amount of resistance, the voltage due to an arcing ground can be only of the order of two and a half times the line to neutral voltage. The cases of conditions of overvoltage due to running away of machines, etc., are extremely rare. Excluding, therefore, the cases of arc-overs due to particularly bad local conditions such as particularly bad conducting dust or soot, we get as the principal cause for flashover, impulse voltages. The switching surges will, at the maximum, be of the order of five and one-half times normal, but voltages so high will be very rare, which means again that the principal high voltages to insulate for are the voltages due to lightning.

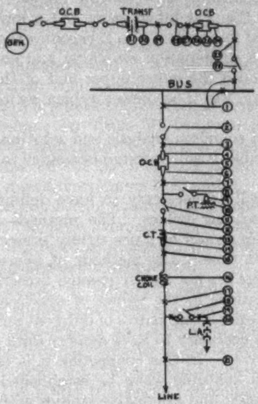

Fig. 2—Typical High-Voltage Station

| | |
|---|---|
| 1 | Bus and bus tap insulators |
| 2 | Disconnect on bus |
| 3 | Insulator—line side bus disconnect |
| 4 | O. C. B. bushing—bus side |
| 5 | Oil circuit breaker |
| 6 | O. C. B. bushing—line side |
| 7 | Insulator—line side O. C. B. |
| 8 | Disconnect—on P. T.—line side O. C. B. |
| 9 | Bushing on P. T. |
| 10 | Potential transformer |
| 11 | Disconnect—line side O. C. B. |
| 12 | Insulator—line side O. C. B. disconnect |
| 13 | Current transformer |
| 14 | Bushing on C. T. |
| 15 | Insulator—lineside C. T. |
| 16 | Choke coil |
| 17 | Insulator—lineside choke coil |
| 18 | Disconnect on L. A. |
| 19 | Insulator on sphere-gap |
| 20 | Insulator on L. A. tap |
| 21 | Line insulator |
| 22 | Disconnect on bus |
| 23 | Insulator—O. C. B. side disconnect |
| 24 | O. C. B. bushing—bus side |
| 25 | Oil circuit breaker |
| 26 | O. C. B. bushing—transformer side |
| 27 | Insulator—transformer side O. C. B. |
| 28 | Disconnect — transformer side O. C. B. |
| 29 | Insulator—transformer side disconnect |
| 30 | Power transformer H. T. bushing |
| 31 | Power transformer H. T. winding |

Let us consider a power system transmission chain, list all the apparatus and equipment and, if possible, see whether or not a definite system of grading cannot be worked out for the various insulation members.

In Fig. 2 there is shown in diagrammatic form the various portions of such a chain. Fig. 2 as it stands, is representative of a typical high-voltage generating station with a generator and a transmission line connected to the bus. It will be seen that some of the parts have been rather finely subdivided in Fig. 2, the reason being that it was thought that, in the first analysis, it would be best to go the limit in the subdivision of parts, and later consolidate such members as could be placed in the same class.

If the generator shown on the low side of the transformer in Fig. 2 is taken away and a low-voltage bus substituted for it, then Fig. 2 becomes the typical diagram for a combination switching and stepdown substation, and if the entire upper half of the diagram is taken away, Fig. 2 becomes a typical switching station diagram.

Before a complete analysis and solution of the problem is possible, it will be found necessary to have further data:

1. It will be necessary to have definite power-frequency flashover values. The methods of obtaining these values should be more rigidly prescribed than at the present time. The methods of measuring at the present time are not rigidly enough prescribed and too great variations in the values of practically identical apparatus exist in the figures of different manufacturers.

2. It is necessary to have definite data on the lightning flashover. In this connection it is essential that a standard lightning wave be established at present. Until complete and exhaustive studies with the Dufour oscillograph show definitely what lightning is, it is essential, if confusion is to be avoided when the lightning or impulse flashover is discussed, that it mean a definite thing. This will clear up the present situation where each manufacturer or each laboratory man is his own lightning maker, and utilizes his own ideas as to what constitutes a lightning or impulse wave. A method of measuring this particular wave should be definitely agreed upon. If so much is accomplished, it should be possible to go one step further and reach a definite understanding with the manufacturers that such data are necessary for design and that they agree to furnish such data to the users of their equipment.

3. More work will have to be done on the characteristics of switching surges. Numerous data are available now with regard to the magnitude of switching surges but further data are needed with regard to their frequency or their characteristics, and as to whether their effect on insulation approaches more closely to that of lightning or impulse wave, or more closely to the power frequency.

4. More data are necessary on the protective features of the design of the stations themselves and particularly on the protective effects of various possible incoming line arrangements, of arrangements of apparatus with regard to structure, and on the protective values of lightning arresters.

TABLE V

RATED RELATIVE IMPORTANCE OF APPARATUS ON LIGHTNING VOLTAGE CONSIDERED FROM POINT OF VIEW OF

A. Minimum number of interruptions
B. Minimum danger of complete interruption
C. Minimum cost of repairing damaged apparatus

PROPOSED GRADING—STRONGEST INSULATION (1) TO WEAKEST (31)

| Columns 1 Order of insulation strength | H. T. Generating station | | | H. T. Switching station | | | Step down & switching station | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2 A | 3 B | 4 C | 5 A | 6 B | 7 C | 8 A | 9 B | 10 C |
| 1 | 21 | 1 | 31 | 21 | 1 | 5 | 21 | 1 | 31 |
| 2 | 20 | 2 | 25 | 20 | 2 | 10 | 20 | 2 | 25 |
| 3 | 18 | 22 | 5 | 18 | 3 | 13 | 18 | 22 | 5 |
| 4 | 19 | 3 | 10 | 19 | 4 | 4 | 19 | 3 | 10 |
| 5 | 17 | 23 | 13 | 17 | 5 | 6 | 17 | 23 | 13 |
| 6 | 16 | 4 | 30 | 16 | 6 | 9 | 16 | 4 | 30 |
| 7 | 15 | 24 | 24 | 15 | 10 | 14 | 15 | 24 | 24 |
| 8 | 14 | 5 | 26 | 14 | 13 | 1 | 14 | 5 | 26 |
| 9 | 13 | 25 | 4 | 13 | 9 | 2 | 13 | 25 | 4 |
| 10 | 12 | 31 | 6 | 12 | 14 | 11 | 12 | 31 | 6 |
| 11 | 11 | 30 | 9 | 11 | 7 | 8 | 11 | 30 | 9 |
| 12 | 8 | 26 | 14 | 8 | 8 | 3 | 8 | 26 | 14 |
| 13 | 9 | 28 | 1 | 9 | 11 | 7 | 9 | 28 | 1 |
| 14 | 10 | 29 | 22 | 10 | 12 | 12 | 10 | 29 | 22 |
| 15 | 7 | 27 | 28 | 7 | 15 | 15 | 7 | 27 | 28 |
| 16 | 6 | 6 | 2 | 6 | 16 | 16 | 6 | 6 | 2 |
| 17 | 5 | 13 | 11 | 5 | 17 | 17 | 5 | 13 | 11 |
| 18 | 4 | 14 | 8 | 4 | 20 | 20 | 4 | 14 | 8 |
| 19 | 3 | 10 | 23 | 3 | 18 | 18 | 3 | 10 | 23 |
| 20 | 2 | 9 | 27 | 2 | 19 | 19 | 2 | 9 | 27 |
| 21 | 1 | 8 | 29 | 1 | 21 | 21 | 1 | 8 | 29 |
| 22 | 22 | 7 | 3 | | | | 22 | 7 | 3 |
| 23 | 23 | 11 | 7 | | | | 23 | 11 | 7 |
| 24 | 24 | 12 | 12 | | | | 24 | 12 | 12 |
| 25 | 25 | 15 | 15 | | | | 25 | 15 | 15 |
| 26 | 26 | 16 | 16 | | | | 26 | 16 | 16 |
| 27 | 27 | 17 | 17 | | | | 27 | 17 | 17 |
| 28 | 28 | 20 | 20 | | | | 28 | 20 | 20 |
| 29 | 29 | 18 | 18 | | | | 29 | 18 | 18 |
| 30 | 30 | 19 | 19 | | | | 30 | 19 | 19 |
| 31 | 31 | 21 | 21 | | | | 31 | 21 | 21 |

## VI. PROPOSED SYSTEM OF GRADING

In Table V there has been set up a proposed system of grading for every member shown in Fig. 2, considered as a generating station, as a straight switching station, and as a step-down and switching station. In the setting down of orders of importance certain assumptions have been made. These are as follows:

1. That the station has two buses.

2. That there is a transfer or inspection oil switch available at the station.

3. That in case of a lightning impulse or discharge coming into the station, which is sufficiently high to spill over, the spilling over at one point or on one piece of apparatus will prevent the impulse with a dangerously high head going any further; that the first spillover would afford sufficient relief, and that the rest of the equipment beyond that point would not be subject to spillover.

4. The effect of a change in the entrance arrangement of ground wires, the effect of the protective values of the bus structure itself, and the effect of the lightning arrester have been entirely neglected. This may be unfair to the lightning arrester, perhaps, but it was felt that for the purpose of the study it would be best to consider the lightning arrester as an additional

safeguard, rather than as a means of definitely reducing the value of the impulse voltage to which apparatus may be subjected.

Referring again to Table V, columns 2, 3, and 4, consider the high-voltage generating station from viewpoints A, B, and C. In the case of viewpoint A it has been assumed that the source of the high-impulse voltage is the transmission and that it becomes lower as it travels into the station. This, of course, takes no account of reflections and re-reflections but it is necessary to do that if the problem is to be considered at all. Viewpoint B is based on the assumption that if an insulator on the bus fails a complete interruption will result. The installation of bus sectionalizing switches, however, results in no such complete interruption. In that case, however, instead of considering the bus as a whole, if the problem is confined to a particular bus section the assumption just made still holds true. In C it has been assumed that the most expensive piece of apparatus to repair on failure is the power transformers and that in general when an oil-filled piece of apparatus such as the current or potential transformer, is damaged, then it will generally be a more expensive matter to repair than the damage to a mere insulator on the disconnect switch.

With these assumptions known, it is plain why, in the case of column 2, the highest insulation value has been assigned to the member 21, and the lowest to member 31. In the case of column 3 on the other hand, it can be seen why the highest insulation strength has been assigned to member 1 and the lowest to member 21. In the case of Column 4, the highest insulation strength has been assigned to member 31 and again the lowest strength to 21. It is not believed necessary to go into a detailed explanation of the reason for the relative order of the intervening members as it is felt with the explanation of the assumptions and the basis of reasoning employed the remaining positions will be obvious upon study. Columns 5, 6, and 7 analyze the order of insulation strength for a switching station from the viewpoints A, B, and C respectively, and Columns 8, 9, and 10 show a proposed grading system for a combined step-down and switching station from the same points of view also, that is from points A, B, and C.

Examining Table V a little more carefully, one will see that the order of grading for a particular point of view is not very different for the various stations; that is, it is practically the same for the generating station as for the switching station, and altogether the same for the generating station and the combined step-down and switching station. Obviously Table V does not offer, as it stands, a practical setup. There are altogether too many members and it is not conceivable that a grading system could be worked up with 31 members and yet have a practical difference in insulation values between them. In Table VI the total number of 31 members has been reduced to 15 and values assigned to each member on the basis of its position in Table V. These are shown on columns 1, 2, and 3. In column 4 the position numbers of a particular member in columns 1, 2, and 3 has been averaged and on the basis of that average a suggested arrangement for general conditions has been worked out in column 5.

An inspection of column 5 reveals an interesting setup. It shows that from the standpoint of general minimum disturbance and minimum damage to the system, the internal make-up of the oil switch ought to be the strongest, that the bus insulators ought to come next and the power transformer windings next, the oil switch bushing next in strength and so on until we get to the insulation of the gaps on the lightning arresters which ought to be lowest down in the series. It shows further, for example, that in general the power transformer bushings ought to occupy a place two-thirds down toward the low end of the insulation chain as against the first position that they undoubtedly occupy on many systems today. It shows that while the line insulators are not to be the very lowest in insulation value they should be very close to that, their position in

TABLE VI

GRADING INSULATION FOR LIGHTNING IMPULSE SURGES

1 = Highest insulation down to 15 = Lowest Insulation for Results Indicated

| Column | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Member | Apparatus | Min. no. of interruptions | Min. danger of complete interruptions | Min. cost of apparatus repair | Ave. position from columns 1—2—3 | Suggested for general conditions |
| A | Oil switch (internal make-up) | 13 | 4 | 2 | 6-1/3 | 1 |
| B | Insulators—Bus side of oil switches | 10 | 1 | 9 | 6-2/3 | 2 |
| C | Power transformer windings | 15 | 5 | 1 | 7 | 3 |
| D | Oil switch bushings | 12 | 3 | 6 | 7 | 4 |
| E | Potential transformer windings | 9 | 9 | 3 | 7 | 5 |
| F | Disconnects—Line side of oil switches | 3 | 7 | 11 | 7 | 6 |
| G | Insulators—Line side of oil switches | 2 | 8 | 12 | 7-1/3 | 7 |
| H | Current transformer windings | 7 | 11 | 4 | 7-1/3 | 8 |
| I | Disconnects—Bus side of oil switches | 11 | 2 | 10 | 7-2/3 | 9 |
| J | Power transformer bushings | 14 | 6 | 5 | 8-1/3 | 10 |
| K | Potential transformer bushings | 8 | 10 | 7 | 8-1/3 | 11 |
| L | Current transformer bushings | 6 | 12 | 8 | 8-2/3 | 12 |
| M | Insulators on line | 1 | 15 | 15 | 10-1/3 | 13 |
| N | Choke coils | 5 | 13 | 13 | 10-1/3 | 14 |
| O | L. A. sphere-gap insulators | 4 | 14 | 14 | 10-2/3 | 15 |

the table where the lowest value is represented by 15, being 13. Finally this establishes in general an order of insulation strength from which some practical setup can be made.

TABLE VII
PROPOSED INSULATION CHAIN

| Rationalized order of insulation Col. 5-Table VI | Apparatus | Suggested order of links in chain |
|---|---|---|
| 1 | Oil switch internal make up | 1 |
| 2 | Insulators—Bus side of oil switch | |
| 3 | Power transformer windings | 2 |
| 4 | Oil switch bushings | 3 |
| 5 | Potential transformer windings | |
| 6 | Disconnects—Line side of O. S. | |
| 7 | Insulators—Line side of O. S. | |
| 8 | Current transformer windings | |
| 9 | Disconnects—Bus side of O. S. | |
| 10 | Power transformer bushings | |
| 11 | Potential transformer bushings | |
| 12 | Current transformer bushings | |
| 14 | Choke coils | |
| 15 | L. A. sphere gap insulators | |
| 13 | Insulators on line | 4 |

SUBDIVISION OF LINKS

1 A—Oil switch (exclusive of bushings)
1 B—Bus insulators—(suspension or strain)
1 C—Bus insulators—(Post type)
2 A—Power transformers (exclusive of bushings)
3 A—Bushings and disconnects
3 B—Transformers (C. T. & P. T.)
4 A—Short section of line nearest S. S. (About 1 mile).

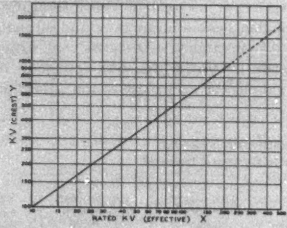

FIG. 3—TRANSMISSION LINE INSULATION BASED ON PRESENT PRACTISE $Y = 18.3\,x^{0.742}$

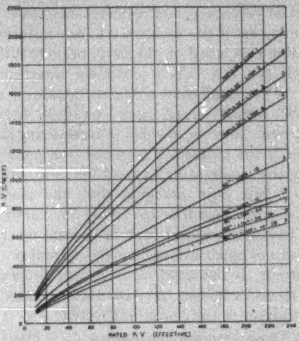

FIG. 4—PROPOSED GRADING OF TRANSMISSION SYSTEM INSULATION STRENGTHS

Showing impulse and 60-cycle flashover or breakdown voltages. For references to links, see Table VII

This has been done in Table VII. Here the 15 members of Table V have been consolidated into four groups and it will be noticed that the grouping in Table VII follows almost entirely the order indicated in Column 5 of Table VI, the one exception being that of the insulation of the line itself. Table VII then proposes that the insulation on a transmission system should be divided into four groups and that the insulation of these groups follow a definite order,—that the insulation of the oil switches and the bus should be highest and the insulation of the line should be lowest. (By line insulation is meant of course only that portion of the line which can be considered from the standpoint of the substation itself. Obviously the insulation of the remainder of the line is an independent problem in economics. If sufficient money is spent, sufficient line insulation can be provided to prevent even the highest lightning voltage from flashing over. This phase is of course not considered here.) Table VII further suggests that the insulation of a group of members in the transmission system consisting of oil switch bushings, potential transformers, disconnect switches, current transformers, etc., be all held at the same level. These four groups are subsequently referred to as the four links.

## VII. PROPOSED INSULATION SYSTEM

In Fig. 3 the data of curve No. 6 of Fig. 1 have been plotted on logarithmic coordinates and a balanced straight line drawn through the values. The equation of this line is

$$Y = 18.3\,x^{0.742} \tag{1}$$

where $Y$ = the crest value of flashover in kv.,

and $x$ = r. m. s. of the line voltage in kv.

The same curve is plotted on regular coordinates as curve 13 in Fig. 1. Using an impulse ratio of 1.8 we get curve 14 in Fig. 1 as the impulse flashover value of line insulators for average present practise. The equation of this curve is

$$Y_i = 32.9\,x^{0.742} \tag{2}$$

Where $Y_i$ is the impulse value and all other values are the same as in equation (1).

In Fig. 4 curves No. 1 to 4 have been proposed for grading the four links shown in Table VII. These curves represent the breakdown or flashover values of the various links and are based on the following:

a. Starting out with curves No. 4 as 100 per cent the other curves have been raised by 10 per cent in terms of curve No. 4 so that curve No. 1, for example, represents at every point 1.3 times the values in curve No. 4.

b. The line insulation developed in Fig. 3 and shown as curves 13 and 14 in Fig. 1 has been adhered to for the insulation of that portion of the lines affecting the substations. On the assumption that a 20 per cent differential would be allowed between the insulation of the line adjacent to the substation and the insulation of the line proper this made curve 14 of Fig. 1 and curve 2 of Fig. 4 identical.

c. Curves 1 to 4 in Fig. 4 do not take into account 60-cycle strengths or tests.

The development of 60-cycle strength has, however, been carried out in curves 5-9. These are based on the impulse strength shown in curves 1-4 and the relationships are as follows:

Curves 9, 5, and 6 give the 60-cycle strength of link 1, parts A, B, and C respectively.

Curve 8 gives the 60-cycle strength of link 2.

Curves 8 and 9 give the 60-cycle strength of link 3, parts A and B respectively.

Curve 7 gives the 60-cycle strength of link 4.

The values of 60-cycle strength are based upon the best available information at the present time on impulse ratios. Where the 60-cycle strength of a particular link has been split into two or more parts, this was done because the different members naturally had different impulse ratios. This clearly shows up the fact that while rationalization is possible for insulation value on the basis of lightning strength and while it may be possible to reduce the number of links in an insulation chain to as low a value as 4, as soon as 60-cycle strength is considered the problem becomes more complicated, the reason being, of course, the different impulse ratios of the different classes of material. The determination of the ratios employed will be evident from an inspection of the curves.

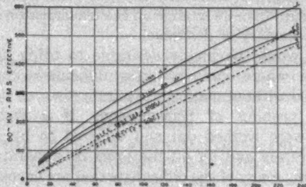

FIG. 5—60-CYCLE EFFECTIVE VOLTAGE BREAKDOWN OF LINKS AND A. I. E. E. TEST SPECIFICATIONS

In Figs. 5 and 5A the curves of 60-cycle strength developed in Fig. 4, have been transposed and plotted in terms of r. m. s. values on both coordinates. The A. I. E. E. tests corresponding to apparatus represented by link 3-A are shown in curve No. 2 (dotted) by links 2-A and 3-B in curve No. 5, by links 1-A and 1-C in curve No. 8, and by link 3-B in curve No. 10 (dotted). In analyzing these curves it will be seen that while it is possible to rationalize and to work out a system of insulation strength with comparatively few links in a particular chain the problem is not quite as simple when the 60-cycle strength is considered. Further, it is definitely clear that in so far as present A. I. E. E. tests are concerned, the buying and specifying of equipment on the basis of these tests will result in a system of insulation that is far from rational as far as impulse or lightning strength is concerned. It shows again that if a system such as proposed in Fig. 4 were adopted, in voltages up to approximately 150 kv. a considerable increase in 60-cycle strength and test is necessary if the proper impulse strength is to be obtained on equipment such as transformers. This may appear objectionable and will naturally be raised as an argument against the system but the objection is valid only so long as present systems of design are followed. As soon as it is definitely recognized that strength in two directions is required, the designer of equipment will be in a much better position than he is today, for he will be able to design for requirements of actual line service rather than along the present lines, where he designs for one thing, *i. e.*, 60-cycle strength, whereas what is needed is impulse strength.

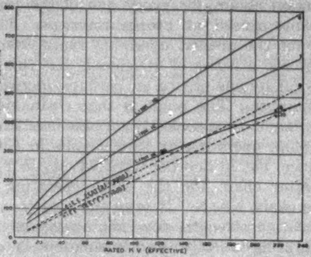

FIG. 5A—60-CYCLE EFFECTIVE VOLTAGE BREAKDOWN OF LINKS AND A. I. E. E. SPECIFICATIONS

A thorough revision of the standards with regard to 60-cycle strength and 60-cycle tests, will be necessary before complete rationalization can be accomplished. No attempt will be made to attack this particular problem at this time. Leaving, however, the 60-cycle tests as they are, it should still be possible to work up a rationalized system of insulation strength under impulse conditions and it should be unnecessary, if the system is a proper one, to disturb it in any way when finally the 60-cycle end is rationalized.

Keeping this in mind, the writer suggests the system shown by curves 1 to 4, Fig. 4, as fulfilling the necessary requirements. Mention has previously been made of the fact that as long as apparatus and insulation strength are specified and bought on the basis of normal or line voltage, difficulty will be encountered in utilizing on a system of a definite voltage, apparatus that might have a nominal rating of a considerably higher voltage. This difficulty could definitely be avoided if apparatus were bought on the basis of normal operating voltage and with insulation strength of a certain definite chain. To amplify: suppose, referring again to Fig. 4, a series of insulation chains were drawn up as shown in Table VIII. This table offers a series of insulation chains for every one of the four links, with chains spaced at proper intervals. The table suggests for the present operating range from 25 kv. and upwards, a series of 10 chains, but this number could be cut by one or two or, perhaps, increased by a similar number. The point is that chain No. 4, for example, might be a perfectly suitable insulation chain for a system operating at 69,000 volts in California, for instance, but in another territory, say in Florida, a much better chain for the same operating voltage might be chain No. 5. If once the idea is embraced that insulation strength does not always go together with operating voltage and insulation is specified independently of operating voltage, then it will be possible to realize the ideal of obtaining, for each system, the insulation strength really necessary. In Table VIII nominal kilovolt classes have been purposely indicated but there is really no valid reason why these should be adhered to or why these should appear in any specifications or in any of the design calculations.

TABLE VIII
IMPULSE VOLTAGE FAILURE FOR PROPOSED INSULATION CHAINS

| Insulation chain no. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Nominal kv. class | 25 | 37½ | 50 | 70 | 90 | 115 | 145 | 175 | 205 | 237½ |
| Link no. | All values below in crest kv. | | | | | | | | | |
| 1 | 382 | 526 | 639 | 819 | 985 | 1185 | 1405 | 1620 | 1830 | 2020 |
| 2 | 353 | 486 | 592 | 756 | 910 | 1095 | 1296 | 1495 | 1686 | 1870 |
| 3 | 324 | 445 | 542 | 693 | 834 | 1005 | 1190 | 1370 | 1548 | 1715 |
| 4 | 294 | 405 | 492 | 630 | 757 | 912 | 1080 | 1245 | 1405 | 1555 |

## VIII. PRACTICAL APPLICATION OF SYSTEM AND RESULTS EXPECTED

If a system of insulation such as proposed in Table VIII or a similar system were adopted, it would result in benefits in many directions. Among these are:

1. The problem of designing the insulation for a system would be considerably simpler than it is at present. Once having decided on the insulation strength necessary on one of the important links, the particular chain into which the entire system insulation is to fall would be determined automatically. The problem of specifying the insulation for the various pieces of apparatus would then become one of simply specifying a certain definite insulation chain.

2. From the purchasing of apparatus standpoint it would mean the placing of the various manufacturers on a more even competitive basis. It would give greater assurance of getting the best purchase for a given amount of money.

3. The establishment of a definite number of classes will result in simplifying and reducing the number of insulating units and insulating classes offered, and will therefore result in a reduction of cost with benefits both to the manufacturer and to the user of apparatus.

4. Without treating every substation insulation problem as a special problem to be long studied, it would be possible to get a correct solution and one that would be reasonably certain to work right under practically all conditions in so far as insulation is concerned.

5. The final effect of all the above would be a great improvement in the type of service rendered by the transmission system.

## IX. SUMMATION

The problem of rationalizing the transmission system insulation is greater than can be covered within the scope of one paper. The writer believes, however, that he has shown that:

1. The present status with regard to insulation practise and standards is not satisfactory. This is as true with regard to the manufacturing of apparatus, the application of apparatus, as it is with regard to the various rules and regulations issued by state and other regulatory bodies.

2. There is no single cause for the present situation, but there are many contributory factors, some of which were perhaps unavoidable.

3. The net effect of the present status is one of confusion in regard to the specification and the purchase of insulation value. Further, the problem of designing a system that is properly correlated in insulation strength is extremely difficult. This results, in the long run, in more trouble on the transmission system than is necessary or desirable.

4. It would be highly desirable to bring about a condition where some of these difficulties could be eliminated without making a separate research problem of each problem of transmission. If a system of grading were worked out and adhered to by all the manufacturers and by all the users of apparatus and equipment, many of the difficulties that are encountered today in the problem of making the transmission system give continuous service would be done away with.

5. Before such a state can be reached it will be necessary to obtain considerably more information or data bearing on the problem. It will be necessary to have more exact data with regard to the characteristics of switching surges and of lightning waves, and a definite agreement as to how these various quantities are to be measured,—in other words, standards for each.

6. Assuming that all the data outlined in 5 are

obtained, a method of arriving at the order of grading of insulation can be formulated. A specific system was actually worked out. It is possible by proper consolidation of various members to reduce the links in a transmission chain that will be graded from each other to a reasonable number. A system composed of four links was proposed. While four links are adequate from a lightning standpoint, from the power frequency standpoint the problem is considerably more complicated due to the different impulse ratios. This problem will require further study.

7. Without changing for the present the specifications covering power frequency strength, a series of insulation chains can be worked out that will be properly graded from the standpoint of lightning strength. A definite series of that type was proposed. By elimination of nominal operating voltages the probability of obtaining proper insulation strength will be enhanced in many cases.

8. If the systems proposed are adopted the ultimate result ought to be less expensive and more satisfactory design, in other words, better continuity on the transmission system as a whole.

Acknowledgment is due to Mr. I. W. Gross for his help in preparing some of the data and in drawing up the numerous charts and tables.

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# Discussion

## RELATION BETWEEN TRANSMISSION-LINE AND TRANSFORMER INSULATION

(Lewis)

## RATIONALIZATION OF TRANSMISSION-SYSTEM INSULATION STRENGTH

(Sporn)

New Haven, Conn., May 9, 1928

**V. M. Montsinger:** The authors of these papers have pointed out the desirability of setting up standards for grading the various apparatus according to their impulse-voltage strengths and have shown the haphazard way in which this work has been done in the past. Their plea for a more rational method should receive very careful consideration.

I do not believe that there is any argument as to whether or not the relative values of the insulation of transformers and the various adjacent apparatus should be put on a more rational basis. The important question is how shall the grading be done? There are two phases to this problem. First, what should be the difference between, say the transformer impulse strength and the arc-over strength of the adjacent line insulation, etc.; and second, what is the most convenient and practical method of expressing the impulse strengths or the relative strengths of the various apparatus?

It is from the second standpoint only that I wish to discuss these two papers. I shall for the sake of simplification confine my remarks to transformers and adjacent line insulators.

Naturally, the first thing that the operating engineer asks for is the impulse breakdown values of the transformer windings and the flashover values of bushings and line insulators. It is, of course, well known that the impulse breakdown of insulations, either of solids, oil, or air, is dependent entirely on the kind of wave used and whether breakdown occurs on the rising front at the crest or at some point beyond the crest, generally called the tail of the wave. Therefore, for the impulse strength to mean anything at all it is necessary to define the wave. A standard wave, of course, could be set up but it would mean that everybody who desired to make a test must have the same kind of a lightning generator, which of course is impractical. Furthermore, it is not practical to test a transformer winding with impulse voltage to check its impulse strength. Neither is it desirable to subject a winding to an impulse voltage in value anywhere near its failure point on account of the possibility of causing injury which might not show up until after being placed in service. Therefore, it appears that we must look for some other more satisfactory method.

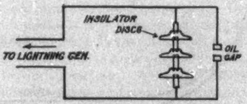


Fig. 1—Set-Up for Comparing Breakdown of Oil and Arc-Over of Disks on Front and Tail Impulse Wave

Let us consider first the adjacent line insulators and their characteristics with respect to impulse flashover at different points on the wave. Tests conducted with Mr. Peek's lightning generator have shown that within practical limits the flashover impulse ratio of an insulator varies with different waves in about the same order as does the breakdown of insulations.

To illustrate what I mean a typical case will be given. Fig. 1 herewith shows an oil gap shunted with three standard 10-in. disks. When an impulse voltage, whose maximum value was approximately twice the flashover value of the insulators, was imposed, the disks naturally cut off the wave, provided the oil-gap setting was not too close. The oil gap was then adjusted to cause one-half of the breakdowns to occur across the oil gap. Sphere gap measurements showed that the disks limited the wave to about 600 kv. The oil gap was then widened and the imposed wave lowered until flashover did not occur until a point beyond the crest of the wave had been reached. To cause one-half of the breakdowns to occur across the oil gap the electrode had to be brought back to practically the same setting as before. The maximum value of the wave in this case was around 450 kv. as determined by sphere gaps. The time in the two cases ranged from a fraction of a micro-second to several micro-seconds. Similarly the same phenomenon was found when solid insulation was used in place of the oil gap.

This, of course, means that a string of insulators can be used as a yard stick for comparing or expressing impulse strengths of transformer windings. Or, in other words, if we know the proper relation between the impulse strength of a given number of line insulators and a given voltage transformer, it is not necessary to know or to give the impulse values of either.

Furthermore, it would eliminate the necessity of defining the wave, for the reason that if the proper relationship is known on one part of the wave approximately this same relationship holds for another part of the wave. Of course, there is a limitation to this in that the two curves of impulse strength versus time are not exactly parallel but cross and diverge as the waves approach the 60-cycle peak value as shown in Fig. 2 herewith.

If all insulator disks had the same spacing it would be satisfactory to express normal line insulation in terms of the number of disks. However, since the spacing of disks may vary considerably, some being as low as 4¾ in., while the standard spacing is 5¾ in., and since both the 60-cycle and impulse flashover strengths of a string of insulators is within reasonable limits a function of the vertical height, and furthermore since both the dry and wet impulse strengths are the same, it is entirely practical to express line insulation in terms of 60-cycle dry arc-over values. This enables any manufacturer or operating company to check the tests.

Referring to the recommended line insulation in Table IX of Mr. Lewis' paper, it will be noted that the 60-cycle arc-over is considerably higher than the 60-cycle tests on the transformer corresponding to twice line voltage plus 1000 volts. This does not mean from the standpoint of impulse voltages the arc-over of the insulator is stronger than the transformer windings, for the reason that the impulse ratio of breakdown of air is considerably less than the impulse ratio breakdown of transformer windings. This difference plus the factor of safety between the tests and actual breakdown of windings makes the transformer stronger than the recommended line insulators. This applies, of course, to fully insulated and not to 2.73 or reduced insulation transformers. In fact, experience has shown that fully insulated transformers have given very satisfactory service when used with normally insulated lines.

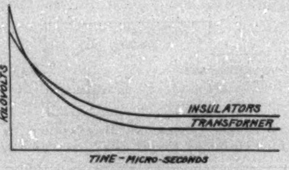


FIG. 2—VARIATIONS OF IMPULSE STRENGTHS OF INSULATORS AND TRANSFORMER INSULATIONS

So far as the transformer is concerned the insulation in the windings should also be given in terms of 60-cycle tests. The reason why this can be done is because many tests have shown that very nearly the same impulse ratio holds for oil alone, puncture of solid, puncture of combinations of oils and solids, creepage over solids, and finally, breakdown of transformer windings, either of interleaved type or concentric type. It is indeed fortunate that this is so; otherwise, if the different insulations and different arrangements of insulation gave widely different impulse ratios it would be an impossibility to express the impulse strength in terms of 60-cycle tests. Not only should it be expressed in terms of 60-cycle voltage but the transformers should be so tested. This makes it possible for all manufacturers to be on a fair and comparable basis and assures the customer of what he is getting.

The impulse strength of the transformer bushings and terminals can be expressed also in terms of 60-cycle dry flashover if it is desirable to grade its impulse strength in reference to that of the other apparatus.

In summing up, the main point which I wish to bring out is that it is not practical and, in fact, not necessary to attempt to give impulse values for the strength of transformer windings and the impulse flashover values of bushings and insulators, but that the desired purpose is accomplished in a more satisfactory manner if 60-cycle dry flashover values of insulators can be standardized as the yard stick for judging the impulse strength of the transformers.

**W. L. Lloyd, Jr:** The subject of rationalization of insulation is not a new one. However, the limited knowledge available (for example, *The Effect of Transient Voltgages on Dielectrics*, F. W. Peek, Jr., TRANS. A. I. E. E., Vol. XXXIV 1915, Part II, p. 1857) has not been utilized as fully as its importance warranted.

Developments have been rapid in the last few years due to a realization that lightning is not a mysterious phenomenon, but that it is a definite thing that can be discussed in an engineering way, studied in the laboratory, and guarded against in the field.

As has been pointed out in the papers, laboratory work and field experience in general show that it is important to design a line so that the conductors are as near to the ground as possible, and that high towers and badly exposed places should be avoided. Similarly, horizontal spacing is preferable to vertical spacing since the average lightning voltage induced on the line is less with horizontal spacing.

Ground wires properly installed and longer insulator strings out on the line can be employed to eliminate flashovers or to reduce their number. Grading-shields or grading-rings on the insulator strings, by raising somewhat, in effect, the lightning sparkover voltage of the insulator string, can be utilized to reduce further the number of flashovers, and prevent damage to the insulators when a flashover occurs.

Long insulator strings should not, however, be brought right up to the station. For a half mile or so from the station recommended insulation should be employed to limit the lightning voltages impressed upon the station equipment. Where dirt or leakage conditions are bad in the vicinity of the station the lightning voltage applied to the station equipment can be more satisfactorily limited by low-set rings on the long insulator strings or by a short air-gap in parallel with the string. To prevent an excessive number of flashovers across these shorter insulator strings, low-set rings, or paralleled gaps, the number of ground wires should be increased over this short section of the line. The proper number of ground wires will give the same factor of safety on this short section of the line with reduced insulation as on the main section of the line with increased insulation but with fewer ground wires. Lightning arresters, if used, should be placed as close to the transformers as possible. The transformer insulation should be stronger than the sparkover voltage of the bushings or the protective gaps at the station.

As suggested by Mr. Montsinger, the strength of the transformer, the sparkover of the bushings, the setting of the gaps, and so forth, should preferably be expressed in terms of the sparkover voltage or number, of standard 10-in. diameter, 5¾-in. spaced, insulator disks, since then any discussion of the shape of the wave, when sparkover takes place, and so forth, does not enter. In this way the laboratory work should be most advantageously utilized by the largest number of operating engineers and we can, at last, proceed with a logical and rational insulation of our transmission systems as we have been attempting to do for so many years and as urged again by Mr. Sporn.

**C. L. Fortescue:** Recent investigations both in the field and in the laboratory indicate that the lightning surge is of appreciable duration. It is estimated that the duration of the effective portion of the wave may vary from a few to 100 microseconds, the longer wavelength having crest values below the 60-cycle flashover of the insulators. Mr. Torok's investigations on the phenomenon of flashover between sphere gaps shows that the speed of propagation of the streamers from sphere to sphere is of the order of one-tenth the velocity of light. Similar tests in connection with strings of insulators indicate a speed of propagation over the length of the string of the order of one-fiftieth the velocity of light. These figures are necessarily approximate and may be subject to modifications as a result of further investigation. However, the results indicate that the time required to complete a flashover due to a surge, after the 60-cycle flashover point has been reached, is, for a string of insulators, of the order of a fraction of a microsecond. Fig. 3 herewith shows the impulse flashover of a string of five standard units and of a string of fourteen standard units for lightning surges of different steepnesses of wave front. The figures are approximate and subject to modification due to further knowledge obtained in the laboratory. We deduce from our laboratory investigations that any lightning wave whose crest reaches the 60-cycle value and exceeds it for a fraction of a microsecond will cause flashover of the insulator string.

The importance of impulse factor to various steepnesses of wave front lies in the fact that the surge potential from a lightning stroke would reach extremely high values if it were not for the flashover limit imposed by the insulator string itself. As a consequence, before the lightning surge has had time to reach anywhere near its crest value it is chopped, or discharged, by the flashover of the insulator string. It is interesting to note that even before the string has reached the flashover point, as indicated by the complete formation of the streamer along the length of the string, the conductivity over the string has increased enormously, so that the leakage current over the string, even before the actual flash takes place, is sufficient to reduce materially the potential of the surge before flashover occurs. When the insulator flashes over, the surge impedance at that point of the line is reduced to practically zero. Consequently, the remaining portion of the lightning surge is reduced to low potential and only the portion of the wave up to the flashover point passes over the line. This portion now is of relatively short duration as compared to the original lightning surge from which it is evolved, and may have a crest value several times the 60-cycle flashover of the insulator string. These chopped waves are of importance because they have this high crest value and may be a source of danger to the apparatus connected to the line.

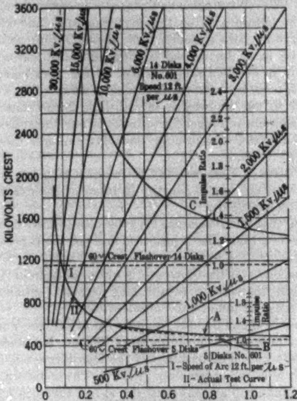


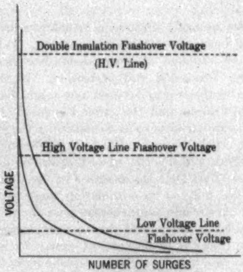
Fig. 3—Voltage Time Flashover Curves of Suspension Insulators

There seems to be a rather widespread misconception of the part played by the time lag of the insulator string in the operation of transmission lines. There seems to be an idea that high impulse factor increases the effective insulation of the line against lightning surges. Many recent tests indicate that any surge due to lightning which goes slightly over the 60-cycle flashover value of the insulator string will cause a flashover. If this be the case, the less the time lag, or the quicker the flashover, the less will be the severity of the surge impressed on connected apparatus. Furthermore, the time lag of an insulator string leads to an undesirable characteristic, namely, the tendency of a string of insulators to cascade. Fortunately, due to the fact that there is this large time lag in the flashover, we are able to make use of an auxiliary device, namely, the arcing ring, which when properly designed will, by improving the field of the insulator, increase the resistance of the string itself to the 60-cycle voltage, and consequently the tendency to flashover may be delegated to the arcing rings themselves which have probably a somewhat lower time lag than the insulator string. This can be done without sacrificing the 60-cycle flashover value of the string itself without the rings. In this way when flashover occurs the arc will form between the arcing rings and no cascading will take place over the string of insulators and as, in general, the power arc will follow the path of the impulse flashover, the use of arcing rings of proper design insures the insulator string against breakage due to cascading. The arcing ring, therefore, has two desirable characteristics: first, it prevents cascading of the string and, secondly, it tends to reduce the impulse factor for a given steepness of wave front. In other words, it gives to the insulator string flashover characteristics more nearly approaching that of spheres.

I should like to bring forward a broader point of view in considering the insulation of transmission lines. It is customary to consider the problem of transmission-line design in two aspects, namely insulation and protection. In the design of apparatus two methods may be used, one might be entitled the method of brute force, and the other the method of properly protecting the various parts so as to distribute the electric forces in the most favorable manner. We do not differentiate between these two methods and describe one as insulation and the other as protection. I feel that the progress in the design of transmission lines has suffered by considering these two aspects independently. As a result, controversies arise due to transmission engineers considering only one of these aspects instead of looking at the problem from the broad point of view. To illustrate this point, let us suppose we have a 220-kv. transmission line insulated with 14 units and we find that with these 14 units the number of outages per 100 miles per line amounts to a certain definite figure, and we wish to reduce this figure to some desirable value. There are two ways in which this may be done. We find that following the one way, which we will designate the method of brute force, we would require an insulator string with perhaps 28 units. This, of course, would mean that the towers would have to be raised at least 6½ ft., the necessary amount depending upon the design of the tower structure. This would in addition involve strengthening the tower to meet the increased stresses due to the added height. The second method would involve adding two ground wires in the proper position over the transmission line, the ground wires having at least one layer of good conducting material and being properly suspended so as to insure against mechanical breakage. Fig. 4 herewith shows that the effect of the ground wires as far as the outage is concerned, is the same as that due to doubling the length of the strings. This conclusion is based on an assumed reduction in the surge potential, due to the ground wire, of 50 per cent. This figure is believed to be conservative. Mr. Peek has obtained much higher values in laboratory tests. These higher values he ascribes to the formation of corona on the ground and transmission wires. However, we assume the conservative value until Mr. Peek's more optimistic values have been established by further tests.

We have here an example of two methods of achieving results desired, both of which will increase the construction cost of the transmission line. However, the advantages of the ground wires are not only due to the reduction of outages of a transmission line but are also due to the reduction of the surge potential and consequent reduction of hazard to apparatus connected to the line. If the first method is used it will be necessary to increase very substantially the insulation strength of the connected apparatus such as transformers, circuit breakers, transformer bushings, outlet bushings, etc., and, also, it would lead to an increased cost in the protective apparatus at the substation. However, a compromise can be made with the over-insulation method by using over-insulation only in the portions of the line exposed to lightning, using the lesser insulation at the unexposed points, but the reduction in outages will not be so great as if the extra insulation is used over the whole line or if ground wires are installed over the whole line. Another modification of these schemes might contemplate using extra insulation and ground wires in combination. For example, extra insulation might be used on portions of the line where grounding conditions aren't very good and ground wires may be used over other portions of the line where ground conditions are favorable and additional ground wires might be used in the neighborhood of the substation.

It will now be apparent that the insulation of the line, which includes so-called protective measures, is an economic problem, the problem of obtaining the lowest outage factor at the lowest cost. The two fundamental principles are the protective principle, such as the use of ground wires, and the principle of over-insulation. These two fundamental ideas can be combined in many different ways so as to obtain the best results. In the final result the effect on the substation apparatus such as transformers, circuit breakers, bushings, etc., must be considered. There are several other methods that are under consideration but have not reached the stage of development where they can be considered as being established. One of these methods is the use of arresters placed at intervals along the line. There is no doubt that if an effective arrester could be placed at each tower the result would be effective. Another method is known as the fused arcing ring. The economy and effectiveness of this method seems to rest almost entirely on the characteristic of the fuse. All these various methods can be considered properly as methods of effectively insulating the transmission line.



EFFECT OF GROUND WIRES

Fig. 4

There has been considerable controversy as to the advantage of using wood-pole construction and preserving the insulating characteristic of the wood pole itself. This of course comes under the heading of over-insulation. A great disadvantage of this method lies in the fact that the surges that are encountered in transmission lines are easily able to shatter, and from all accounts have frequently shattered the wood pole, leading to power outages due to mechanical failure. A modification of this method of obtaining improved insulation is the use of the insulated ground wire in conjunction with the wood pole. This has the advantage of preserving the wood-pole insulation and reducing the surge potentials to which the wood is exposed, thereby preventing a tendency to pole shattering. In the laboratory without lightning generator we are able to shatter wood poles of considerable length. It is easily seen, therefore, how much of a liability this pole shattering is in wood-pole construction where the line is exposed to lightning surge potentials and energies very much in excess of those that can be obtained in the laboratory.

Experience has shown that with certain types of line construction and degrees of insulation certain classes of transformer insulation are satisfactory and give good service. It seems to the writer that the method of classifying required insulation of connected apparatus by the number of units used in the adjacent insulator string is not only a good practical method of specifying the required class of insulation but is also scientific. In the future, the effect of the line construction on connected apparatus will be given more consideration and no doubt the use of special protective measures, such as additional ground wires near the substation, will grow in favor as more and more experience is obtained. The Westinghouse Company is carrying on investigations on lightning with the klydonograph, and expects to do further work with a modification of the Dufour oscillograph. It is hoped that, during the coming lightning season, by the above work in the field supplemented by the work being carried on in the laboratory with the lightning generator, we will materially add to our knowledge of lightning phenomena, thereby enabling us more intelligently to insulate our transmission lines against the effect of lightning, reducing outages due to this source.

**J. F. Peters:** I am heartily in favor of coordination of insulation but I am not so heartily in favor of the exact method suggested by Mr. Sporn.

In order that the insulation may be coordinated it will have to be done on a basis that is practical and not too expensive.

Insulation that goes into high-voltage apparatus, such as circuit breakers and transformers, is quite variable in its insulation strength; therefore, in establishing a chain of gradations this variation must be taken into consideration.

Referring to Chain 5 in Mr. Sporn's Table VII, you would have a line that must stand an impulse of 757 kv. but must fail at less than 834 kv. The bushings of the transformers must stand 834 kv. but must fail at less than 910 kv. The transformer windings must stand 910 kv. but must fail at less than 985 kv.

Now, the range between the values that insulation must stand and those at which it must fail are not large enough for practical application. It is one thing to design apparatus to withstand a certain voltage but it is an entirely different matter to design apparatus to fail at a point slightly higher than a specified value. By increasing those increments to a practicable value I am quite sure the strongest link in the chain will be so expensive that it cannot possibly be justified.

One way of getting around this difficulty that appeals to me as practical is to establish one point in the chain that is definitely weaker than the other links. That weak link logically should be either the line insulation adjacent to the station or some relief gap located adjacent to the station. When such a relief is fixed it would then only be necessary to say that all of the apparatus and substation insulation should be stronger than so much and in specifying this strength I heartily agree with Mr. Montsinger's suggestion of putting it in terms of 60-cycle dry flashover.

In connection with Mr. Lewis' paper, I have had occasion in the last few years to look over quite a few records of surge investigations on actual transmission systems and I have observed that there appear to be two kinds of impulses, one that comes under Class A as listed by Mr. Lewis in Fig. 3, the other as Class C in the same figure, and between these two types there seems to be quite a wide band. I do not have sufficient information to state why this wide band exists but I am inclined to believe that the Class A are due to direct line hits and Class C are due to induced strokes. Now if this is the case, can we draw the conclusions that ground wires will have the same effect on reducing Class A disturbances as they will for Class C? All of the theories concerning ground wires are based on induced strokes and cannot apply to the direct strokes in the same way. There is no doubt that the presence of ground wires will divert many of the direct strokes and in that way will materially protect the line against such disturbances. But will they divert all of the direct strokes? If not, then the installation of ground wires will not produce lightning-proof lines.

**F. W. Peek:** It is significant that in these papers and in the discussion, lightning is expressed in numerical values; it is on an engineering basis. It is now known that the maximum lightning voltage that can appear on a transmission line depends upon the height of the line above ground and whether or not a ground wire is used. The maximum voltage that reaches the station and the apparatus is the lightning breakdown voltage of the line or the lightning arc-over voltage of the insulators. Since the voltage to which the apparatus is subjected is thus determined by the line insulators it is readily seen that it is not logical to use apparatus with a lower lightning breakdown voltage than the line insulators in the vicinity of the station.

An examination of statistics shows that a very small fraction of 1 per cent of transformers is damaged each year by lightning. Thus present transformer insulation is fairly well matched with present average line insulation. It would thus not be economical to add greatly to transformer insulation as long as the present average line insulation is used. However, as better service is demanded it is necessary to over-insulate lines in parts of the country where lightning is severe. If this over-insulation is carried up to the station the transformer strength should be increased in proportion to the increase in the insulation on the line. In many cases it will probably be found that satisfactory operation will be obtained with average insulation in the vicinity of the station and with any desired over-insulation out on the line. The lower insulation near the station on a comparatively short section would usually not appreciably increase the outages. This follows because the chance of an arc-over on a short section is small and further because high lightning voltages are rapidly reduced by corona and other losses before traveling a very great distance on the line. I am quite in sympathy therefore with the suggestions for balanced insulation on lines and apparatus as suggested in the papers by Mr. Lewis and Mr. Sporn.

Mr. Lewis has tabulated the average number of line insulators for various operating voltages and suggests that if the line insulation is increased above the average the transformer insulation should be also increased proportionally. He suggests that this increase be measured by the usual 60-cycle test of the transformer and that the line insulators be expressed not in terms of the number of units used but rather in terms of the 60-cycle arc-over voltage of the insulators. This is quite rational and removes a number of difficulties as to the lightning wave shape used, etc. It so happens that if a line insulator will protect a given transformer by flashover for a given lightning wave it will also protect it for other lightning waves. All this means is that over a wide range of transients the ratio between the lightning breakdown voltage of the insulator and of the transformer remains more or less constant. This follows because the insulator is a time gap or requires time to cause arc-over. It thus automatically takes care of changes in wave shape.

Another advantage of the insulator as a practical means of measuring the lightning voltage of transformers is that the operating engineer knows immediately whether or not the number of insulators on his line is stronger than the transformer.

I do not mean, of course, in endorsing Mr. Lewis' suggestion of using insulators as a measure of lightning strength of transformers that the actual lightning strength for various wave shapes should not be measured in the laboratory. In fact, we have done this very thing.

The following tests are given as illustrations and have particular bearing on the present discussion. Transformers were set up in the laboratory and connected to a transmission line supported by the usual line insulators. Lightning waves from the 3,500,000-volt lightning generator were sent over the line and the strength of the transformers measured in terms of insulator disks as well as voltage. These tests have been made with a number of different types of waves. I am particularly interested in this discussion because in 1915 I presented a paper before the Institute—*The Effect of Transient Voltages on Dielectrics*—covering this subject. In that paper the term "impulse ratio" was first used, as well as the term "micro-second" as applied to time lag and insulation breakdown. In this early work it was not possible to take oscillographs. However, this is now being done in the laboratory and studies have been made on insulator flashovers and insulation strengths with waves varying in length from 1/25 micro-second to several hundred micro-seconds.

By full use of available knowledge, it appears that transmission lines can be made almost or practically lightning proof.

**K. K. Palueff:** To illustrate the great variation in lightning characteristics of existing transmission systems I prepared, some three years ago, a table given below and quoted in part by Mr. Lewis.

| Rated voltages | 66 | 88 | 100 | 110 | 120 | 132 | 220 |
|---|---|---|---|---|---|---|---|
| Total circuit miles...... | 4880 | 717 | 1617 | 2895 | 468 | 882 | 1150 |
| No. of suspension insulators—............... | | | | | | | |
| Minimum........... | 4 | 5 | 5 | 6 | 8 | 9 | |
| Maximum........... | 6 | 7 | 8 | 9 | 9 | 0 | |
| Average............ | 5 | 6 | 6.4 | 7.23 | 8.83 | 9.7 | 13. |
| Height of lowest conductor at the tower—..... | | | | | | | |
| Minimum........... | 22 | 28 | 34 | 25 | 30 | 42 | |
| Maximum........... | 53 | 47 | 55 | 68 | 61 | 55 | |
| Average............ | 35 | 38.5 | 38.7 | 47 | 57 | 46.7 | 55.6 |
| Percentage of total mileage that data are given on—............... | | | | | | | |
| Number of insulators. | 100 | 78 | 100 | 100 | 100 | 100 | 52 |
| Number of conductors | 75 | 100 | 86 | 83 | 100 | 100 | 52 |

Since this table was prepared, the writer has learned of a 66-kv. system having 9 disks on entire line, of a 110-kv. system having 10 disks on entire line, and 15 disks at the substation end, of 132-kv. system having in addition to 9 disks 7.5 ft. wooden crossarms.

It also was found that a great many systems, having a more or less normal number of disks, were using wooden poles and crossarms with ungrounded hardware, which in some cases more than doubled the actual dielectric strength of the line.

Since Mr. Peek's laboratory investigation showed that lightning voltages on transmission lines may often exceed their dielectric strength, it became obvious that line insulation should be used as a measuring stick of dielectric strength of varius apparatus connected to it.

However, study of the line insulation data given above indicates that if such a principle is accepted then transformers and circuit breakers on some systems must be capable of withstanding high-potential test equal to far more than twice line operating voltage. For instance, a transformer for a 66-kv. system, with 9 disks as mentioned above, would require a high-potential test of four times normal (264 kv.). This of course means a substantial increase in cost of the apparatus.

The experience of some operating companies has proved the correctness of this principle, and forced them to buy transformers capable of standing a high-potential test of more than twice operating line voltage for their "over-insulated" lines.

The second group, however, were inclined to attribute the cause of their operating troubles to defectiveness of the apparatus, which attitude deprived them of an opportunity to benefit by their experience.

The third class of engineers, being annoyed by arc-overs of the bushing on circuit breakers and transformers, realized that the dielectric strength of their apparatus was lower than that of the lines, but instead of following the example of the first group they established a habit of securing extra strong bushings matching with line insulation, leaving, however, the apparatus proper at the original strength, thus virtually making the most expensive part of the transmission system the weakest.

It is on account of the above consideration that I most heartily welcome the recommendation of Mr. Sporn's paper.

The important question is how to ascertain the lightning strength of the apparatus. Making an impulse test as part of the acceptance test is at present quite out of the question, for two reasons: first, the range of shapes, and the magnitude of characteristic traveling waves met with in service are not sufficiently well established; second, there is no way of determining the place and degree of partial damage that may be done by such a test to a transformer. It is quite possible to puncture insulation between adjacent turns or even coils, with so little energy concentrated at the point of failure that it would be absolutely impossible to find the latter even after complete disassembly of the transformer.

Transformers respond to impulse, not as a pure inductance, but as a very complicated network of distributed capacitances and inductances. The result of it is that high-frequency voltage may concentrate between adjacent turns or coils.

This phenomenon is excellently described in Messrs. L. F. Blume and A. Boyajian's paper on *Abnormal Voltage within Transformer Windings*, (TRANS. A. I. E. E., Vol. XXXVIII, Part I, 1919, p. 577).

Thus two transformers, equally strong at low frequency (not greatly in excess of 500 cycles), may have quite different lightning strength. In spite of that, however, it seems that the only practical method of making acceptance tests is to subject apparatus to a sine-wave voltage of low frequency (say between 25 and 500 cycles). The value of low-frequency arc-over of the line insulation (which must include wooden cross-arms in case hardware is not grounded) of the system under consideration should serve as a criterion for the magnitude of potential test of the transformer.

**J. F. Peters:** I should like to add a few comments to what Mr. Palueff has stated so as to prevent any possible misunderstanding of the discussion. He gave a very beautiful analytical discussion that applies to an abrupt application of voltage to a transformer winding. His conclusions are what would happen if there were no other factors present except the capacitance and inductance of the windings; but what actually happens in service is quite different. All high-voltage apparatus are equipped with bushings that have high enough capacitance to alter very considerably the internal state of affairs. With a typical high-voltage transformer, if an impulse with a sheer front is applied, the capacitance of the bushings will absorb this impulse to such an extent that it will increase gradually to its full value in something like five microseconds. That being the case, the voltage is applied to the windings slowly enough that it distributes quite uniformly throughout the winding.

**C. D. Gibbs:** (communicated after adjournment) The papers by Mr. Lewis and by Mr. Sporn represent the first serious consideration given to coordinating the insulation of transmission lines with that of equipment. It is a feature that most engineers have encountered, but which, due to lack of data, has largely been settled by guess.

One point which I wish to bring out is that the problem has been started on the premise that the lines must be insulated to prevent flashover during lightning storms. This premise is justified only on some of the higher capacity lines such as the 220-kv. trunk lines where an interruption involves a loss of a large block of generating capacity. On the usual transmission line a circuit can be dropped out of service without upsetting the operation of the system and in these cases there is no justification for the expenditure necessary to make the line lightning-proof.

Too much effort is being made to secure higher and higher flashovers for transmission lines. By the use of wood poles, arms, and braces, the flashover may be doubled but the use of the overhead ground wire reduces the potential which will cause flashover by 50 per cent, so the number of interruptions remains the same in each case. In the former, the terminal equipment will be subject to much greater stresses. The additional cost of the extra insulation at terminals and on the lines must be very carefully weighed against the value of the loss of a line. After the terminal equipment is already established, the line insulation should be such that it does not endanger the equipment. That is, the problem is reversed. Instead of the line insulation being fixed and the transformer insulation determined from it, the transformer insulation is fixed and the line insulation should be coordinated with it.

Mr. Lewis recommends flat spacing of conductors. Such a recommendation is not based on the economics of the case. It has been determined that for a given width of right-of-way, 50 per cent more power can be transmitted at 132 kv. than at 220 kv., by using the conventional two-circuit tower for the 132-kv. line. This value may be further increased by using a three-circuit tower having the conductors in the vertical plane.

Another recommendation is that the flashover of the last one-half mile of line be lower than the rest of the line and additional ground wires installed. It is not apparent why this last one-half mile should be designed to function as an arrester. To do this, additional tower designs will have to be made resulting in an increase in the number of types used on the line with consequent increase in cost. Towers and insulators are very poor arresters. They may be satisfactory in relieving the overvoltage but every flashover is attended by an interruption.

It appears that the arresters should be called upon to perform the functions which Mr. Lewis assigns to the insulators of the last one-half mile of line. If the arresters are of insufficient discharge capacity they should be designed larger. Larger choke coils may be of distinct advantage or the installation of arresters on the bus. In any case, the arresters should not be rendered useless by permitting flashovers that will drop the line out of service when it can be avoided without additional cost.

**C. A. Jordan:** (communicated after adjournment) Despite the general tone of optimism which pervades Mr. Lewis' paper, lightning flashovers have occurred, and probably will continue to occur, on the most strongly insulated lines in service today. Probably a greater percentage of high surges measured on transmission systems by surge-voltage recorders arise from direct strokes to line structures or conductors than is now generally realized. Especially for lines of moderate voltages, it is not to be expected that any amount of insulation or ground-wire protection, within practical limits, will prove effective against these.

By increasing insulation levels of important transmission circuits and installing additional ground wires, much may be done to increase immunity to the average run of severe induced surges; hardly, I believe, as much as Mr. Lewis anticipates, however. For some unexplained reason, the operating history of transmission circuits with ground wires, engineered in accordance with the best modern thought, has fallen short of the bogey set by Mr. Lewis' data. For the past two or three years, numerous and earnest efforts have been made to measure with klydonographs the shielding effect of ground wires on operating circuits, without finding voltage reductions of the order indicated in this paper. In fact, to my knowledge, no reliable records of any considerable reduction have been obtained to date. As the theory of the ground wire is generally understood, it must remain substantially at ground potential to exercise any appreciable shielding effect. Quite apparently, due to impedance in the ground wire and its earth connections, and possibly due to other factors of which we now have no knowledge, field conditions depart materially from laboratory conditions, even in the best of circumstances.

Since flashovers initiated by lightning cannot in the nature of things be avoided, it becomes necessary to exercise such control as is possible over the locations of these flashovers. It is not always easy to incorporate this control as a basic feature of design with confidence. The great difficulty is an almost utter ignorance of the surge impulse strengths, under various conditions, of the insulations commonly employed by the industry. I make this statement advisedly, having some slight knowledge of the research work which some manufacturers and operating companies have been, and are, conducting. Rational design will not be possible until the voltage-time characteristics and rates of fatigue of the common insulations, individually and in the combinations usually employed, have been determined, and the range of surge characteristics to be met with in practise has been established. The application of the cathode ray oscillograph bids fair to supply much of the latter information within the next few years. Laboratories equipped with surge generators should not lag in developing technique and determining the equally important insulation characteristics.

Only lightning discharges within a very limited area surrounding the yard can affect the substation directly. Thus the maximum fundamental value of most surges which can appear in the yard will be governed by the surge flashover voltage (which is variable within wide limits) of the insulators at the line entrance. If the yard and particularly the bus insulators are weaker than the entrance insulators for any surge condition, there is risk of yard flashover causing a station shutdown. If a flashover occurs on the oil circuit breaker bushings, there is usually the same risk. If a surge of dangerous magnitude penetrates the yard still further to the transformers before finding a point of relief, there is possibility of transformer failure. Obviously it is preferable to avoid yard flashover entirely, if possible.

It is because of the present lack of data upon which to base intelligent design, and the gradual realization of what must be done to improve the situation, that the self-protecting transformer has, of recent years, received serious consideration as a forward step in system design. The self-protecting transformer is one in which the internal insulation, taken as a whole, is able to support any potential which can pass the bushing. Granted, bushing failure is undesirable, but as between bushing failure and transformer failure, the former is the lesser of the two evils.

Mr. Lewis now proposes that the insulation strength of transformers to surge potentials be gaged in terms of the 60-cycle flashover voltage of the insulators used on the lines for at least one-half mile immediately adjacent to the station, and suggests limiting values of line insulation for the nominal system voltages 66 kv. and above. I do not believe this proposal, if generally adopted, will best promote the interests of the art. Aside from the obvious advantage of relieving the manufacturer from the development of improved methods of testing with a possible saving in production costs, no other advantage is, for the moment, apparent. On the other hand, the proposal has several serious disadvantages and even dangers.

The relative strengths of insulations vary materially with wave shape. Too little is at present known regarding distribution of surge stress throughout yards and apparatus in general, and transformers in particular, to feel any degree of confidence that all will be well if insulation strengths are graded for 60-cycles alone. Mr. Palueff in his discussion has analyzed this situation very well as regards the transformer.

The restriction of line insulation in a zone a half mile or more around a station has the serious operating disadvantage that it increases the likelihood of unnecessary line interruptions, even though ground wires be used, because advantage cannot be taken of surge attenuation in this zone. Such an extensive arrangement of "impulse spillways" does not seem necessary. A number of operating companies is using one set of protective gaps at the line entrance or elsewhere in their yards with satisfactory performance in limiting the magnitude of surges passing a point.

Modern high-voltage switchyards are usually quite extensive. A line entrance may be 1000 or more feet distant from a transformer bank. Limitation of line insulation at point of entrance would be of little benefit to the distant transformer bank. It is true that such a case is special and protective gaps or lightning arresters should be installed adjacent to transformers, the line insulation no longer being the governing factor. But the point is that a high percentage of installations *would* be special and the proposal to reduce insulation adjacent to the station could not be applied universally, even if it were desired to do so.

The greatest danger to progress would be a tendency, as a path of least resistance, to perpetuate the expression of one thing in terms of something entirely different, and related to it only in a very general and variable way. A sound eventual solution cannot be expected in that manner. The only cure is continued investigation and research. It will cost the industry effort and money, but I believe the expenditure will be more than justified.

**W. W. Lewis:** Referring to Mr. Peters' statement as to the effect of the capacitance of a high-voltage bushing in modifying an impulse which may reach the bushing from a transmission line:

I do not believe that a high-voltage bushing will have very much effect in this respect. This is apparent from the following consideration: An overhead transmission line has a capacitance to ground of the order of 0.010 $\mu$ f. per mi. The capacitance of a power transformer from high-voltage terminal to ground is of the order of 0.002 $\mu$ f. and a high-voltage bushing has a capacitance to ground of the order of 0.0002 $\mu$ f. Thus it will be seen that the capacitance of the transformer itself is 10 times that of the bushing and the latter has a capacitance that is equivalent to only 1/50th of a mile of line. In addition, the station busbars have an appreciable capacitance to ground, in some cases equal to or greater than that of the transformers.

Neither the transformer nor bushing capacitance would have any appreciable effect on a wave of very long duration. A short wave or a wave that had been chopped off by the line insulators would be affected slightly by the combined capacitance of the busbars, transformers, and bushings. The greater effect, however, would be due to the capacitance of the busbars and transformers. The bushings would have an insignificant effect, as they only add a few per cent to the station capacitance.

In considering these matters, we should take account not only of the most favorable cases, but also of the most severe cases. In these cases, we will not be able to lean very heavily on the station capacitance, which is too low to give much protection.

**Philip Sporn:** (communicated after adjournment) I was frankly very much disappointed and surprised at the stand taken by Messrs. Montsinger, Lloyd, Peek, and Peters in regard to the question of actually measuring impulse voltage. They stated it would be better to specify impulse strength in terms of insulators. Disregarding the point that Mr. Peek himself made, that it isn't until you begin to express data or relationships in actual numerical quantitites that you can claim that you are even beginning to talk in a scientific manner, I think there are numerous objections to expressing impulse strength in terms of insulators.

For one thing—and I believe this is the principal objection—there is great danger that by adopting that practise we will only continue the situation that we are confronted with now, which is admittedly bad. The operating people now find that they had been lulled into a false sense of security: they bought equipment that was apparently good for certain voltage and sat back satisfied but later found it was breaking down, and it wasn't breaking down at the voltages for which they bought it but at other voltages. If the equipment is able to stand up for those other voltages they might as well know what magnitude it can stand up to and then they can use their judgment in determining how much of a factor of safety they ought to have.

Another objection to the proposed method of measurement is the fact that when we do express insulation strength in terms of insulators it might get us in trouble under a situation where a wave below the flashover value, say of the bushing of the transformer, comes in and is reflected at the transformer itself.

There is still a further objection, particularly on low voltage where wood lines are used. That is, if you talk of transformers or other apparatus as being good for a certain number of insulators, there is danger it will be taken at its face value, and we are going to have the difficulty that we are confronted with today and which Mr. Palueff brought out, and that is that you might have five insulators on a wooden line but the equivalent insulation strength might be actually 12.

It seems to me several of these difficulties could be eliminated if we started to express these values as actual numbers.

The objection has been raised that we haven't a standard. Well, that is only another good argument for establishing one. Standards have been established with regard to other quantities and can be with regard to this.

I don't think that anybody is particularly anxious to get insulation values down to a point where they will be expressed in such values that the accuracy will be good to plus or minus one per cent, but even though we don't go to such precision it will be still better, I think, to express them in actual numbers.

I think Mr. Fortescue has brought out the fact that the impulse flashover on a wave where the peak isn't reached in less than a microsecond is the power frequency flashover value. That may be so. I don't think there is any agreement on that, and it only brings out a point I have made, that we are still groping blindly and will continue to do so until we get some actual oscillographs on a number of systems, on many systems, and get hundred of oscillograms and find out exactly what lightning is and what its limits are, and so forth.

Mr. Peters has stated that he believes that the conditions today are very good and that, in general, transformers are standing up well, and apparently there is really no reason for disturbing them. I find it difficult to agree with that point of view. You don't have to have ten per cent of your transformers or of your other equipment failing to be in real trouble. For a particular station which may be one out of fifty stations on a system, a failure once a year or once every five years is a very serious matter, and it may cause considerable damage.

Neither do I agree with Mr. Peters in his statement that, if the strengths that were proposed in Table VIII were spaced by a practical amount instead of roughly the ten per cent as was suggested, the link of highest installation would reach so high a value that it would be entirely impractical. I know that in our own company we have now for a period of eleven years on one particularly extensive system been buying transformers considerably over-insulated; in fact, the standard specified has been a three times normal test instead of twice normal—the present A. I. E. E. Standard. Quite regularly, generally once a year, we survey the results of previous years to see whether we want to continue the same policy for the following year or two, and so far we have found it a paying proposition to continue it. I know, too, that we found it necessary to go up to higher insulations than the Institute Standards on some of our other voltages, and I believe there is quite a number of other operating companies doing, or starting to do, the same thing today.

I do not think that the question of rationalizing insulation strength is a particularly easy one, and I certainly did not want to convey the impression that it is. But suppose it isn't. There is a lot of work to be done on it. But if you examine Figs. 1 and 4 in the paper, Fig. 1 showing the present status with regard to insulation and Fig. 4 the proposed arrangement and presumably the status that will exist if the idea with modifications is carried through, I think that there is a good chance that the conclusion will be that all the trouble that may be necessary to bring about the conditions shown on Fig. 4 will have been worth while.

# High-Speed Recorder

BY C. I. HALL[1]
Fellow, A. I. E. E.

***Synopsis.****—This paper describes a new electrical instrument for automatically recording variations of electrical functions at high speed. The rate of chart motion is lower than that of the oscillograph so that the envelope of an a-c. wave is produced. This recorder has been successfully applied in the analysis of breakdowns on transmission lines, giving data used as the basis of securing improved selective relay protection and for other problems involving automatic high-speed recording.*

## INTRODUCTION

THE rapid adoption of interconnection and the formation of complex power networks have made it increasingly difficult to provide adequate relay protection for these systems. The location and settings of selective relays must be such that overloaded or faulty lines are promptly isolated and cut off with a minimum of interference to the service continuity of the remainer of the system. The high-speed recorder is an instrument which has been designed particularly as an aid in the solution of these problems. It has been built in a variety of forms having either one or more recording elements and giving either maximum values only, or records having a time base. It is started automatically by the excessive current incident to the fault and begins to record in approximately 0.03 sec. In its four-element form, it gives simultaneous records of the neutral ground current and each phase-voltage, for a period of 10 sec. after the occurrence of the fault. This covers the life of the disturbance, since the faulty section is usually cut off in a few seconds by the protective relays.

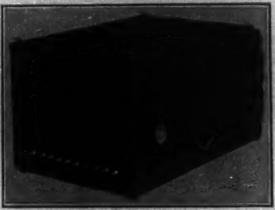


FIG. 1—GENERAL VIEW OF FOUR-ELEMENT RECORDER

Although the high-speed recorder was designed primarily as an aid in the study of line faults, it is obvious that it has numerous other applications, some of which are mentioned later. The recorder may be used in nearly any application in which automatic starting or high-speed recording are necessary.

The use of the recorder in analyzing transmission line faults has been described by E. M. Tingley in a paper entitled *The Hall High-Speed Recorder.*[2] Included in this paper were numerous records made in service on the system of the Commonwealth Edison Company. The purpose of the present paper is to deal particularly with the design and construction of the recorder, including sufficient test records to illustrate the varied application of the instrument.

## REQUIREMENTS OF RECORDER

The design of the recorder incorporates the following features, which are considered essential to a device of this class:

a. Automatic Operation: Recording is started by a high-speed relay actuated by increase in line current or other determining variable.

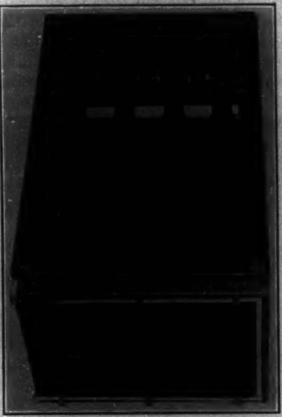


FIG. 2—INTERIOR OF FOUR-ELEMENT RECORDER

b. Speed of Recording: The record shows values for each half cycle on 25- and 60-cycle circuits.

c. Minimum Delay Before Beginning to Record: The total time after occurrence of the fault until the device begins to record is approximately 0.03 sec. It is

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[1] Engineer, General Electric Co., Fort Wayne, Ind.

*Presented at the Northeastern District No. 1 Meeting of the A. I. E. E., New Haven, Conn., May 9-12, 1928.*

[2] *The Hall High-Speed Recorder,* E. M. Tingley, 1928 QUARTERLY TRANS., No. 2, Vol. 47, p. 252.

obvious that this lag must be short in order that no part of the record be lost.

d. Sturdy Construction: Comparable to portable ammeters and voltmeters. The instrument contains no delicate parts which are likely to become damaged with ordinary handling and care.

e. Portability: The recorder may be easily moved about from place to place, and set up in condition for recording.

Fig. 3—Auxiliary Relay for Four-Element Recorder

f. Improved Light Source: The light source is more effective and efficient than types used heretofore. An intensely brilliant point of light is produced on the recording film, yet the input is low, so that dry cells can be used as a power source.

g. Daylight Loading: Standard photographic film holders are used, enabling loading and unloading in daylight as with an ordinary camera.

Fig. 4—Record Made by Four-Element Recorder on System of Commonwealth Edison Company

## Classes of Recorders

As previously mentioned, the recorder has been produced in both four-element and single-element form. Views of the former device are shown in Figs. 1 and 2 while the latter is shown in Figs. 7 and 8.

Fig. 4 shows a chart obtained from a four-element recorder in service on the lines of the Commonwealth Edison Co. The upper record of this chart gives the variation in neutral ground current while the three lower records give voltage values on the three phases. Ordinates represent current and voltage values, and time movement is from left to right.

Fig. 10 gives a group of four calibration records made with a single-element recorder of the stationary film type. With this construction, maximum values only are recorded. The single-element recorder has been arranged also to give time-base records by the application of the moving film mechanism shown in Fig. 9. The latter is contained in a light-tight case which is attached to the top of the recorder proper, taking the place of the ordinary film holder shown in Fig. 7.

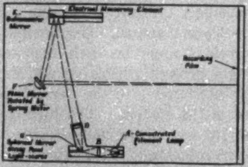
E - Galvanometer Mirror
Electrical Measuring Element
Recording Film
F
Plane Mirror Rotated by Spring Motor
D
C
Spherical Mirror Giving Point Light-source
B
A - Concentrated Filament Lamp

Fig. 5—Schematic Diagram of Light Source and Optical System, Four-Element Recorder. (Side View)

## Light Source

A side view of the four-element recorder drawn schematically is shown in Fig. 5. This cut also illustrates the type of light source used in all recorders. A small concentrated filament automobile type lamp, *A*, is placed in one end of a light-tight tube which also contains lenses *B* and *D* and a highly polished metallic hemispherical mirror *C*. The rays from the lamp are focused upon the hemispherical mirror, which, through reflected light, becomes a secondary light source of very small diameter and high intensity. The rays from this secondary source pass through lens *D* to the galvanometer mirror *E*, from which they are reflected to plane mirror *F* and thence are focused upon the record-

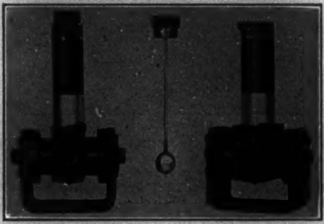

Fig. 6—Electrical Measuring Element. Front and Rear Views and Vane Only

ing film. During the time of recording, the plane mirror *F* is rotated at a definite rate in the direction indicated by the arrow by a governor-controlled spring motor. This rotation of mirror *F* causes the recording point of light to move across the stationary film at the rate of 1 in. per sec. Only one lamp and secondary source are required for all four recording elements, as four lenses *D*, located in an arc of a circle above *C* and transmitting light to four individual galvanometer mirrors are used. This will be understood by referring to Fig. 2.

Fig. 7—General View of Single-Element Recorder

### Electrical Element

A detailed view of a recording element is shown in Fig. 6. This element consists of a soft iron yoke supporting two adjustable poles which carry the winding. The moving element is a soft iron vane, mounted rigidly on the end of a stiff duralumin rod and set at an angle of 45 deg. to the flux path between the poles. An aluminum support riveted to the vane carries a galvanometer mirror and a guide bearing pivot. The vane and mirror assembly is shown between the front and rear views of the complete element. For use on a-c. circuits the electrical elements are connected to the lines through transformers contained within the recorder. In this way, proper ratings are obtained and a standard element can be used for recording either current or voltage. When d-c. circuits are being studied, the transformers are replaced by special external shunts.

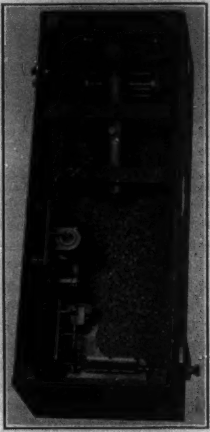
Fig. 8—Interior of Single-Element Recorder

The moving system or vane is of low inertia and high period of oscillation, so that it readily follows changes during each half cycle. In contradistinction to the usual indicating or recording element of standard instruments having a fine hair spring for furnishing the restraining torque, the elements of the high-speed recorder use the torsional force in the stiff duralumin rod mentioned above, to return the element to its zero position. The use of this relatively stiff moving system results in a very reliable element which is not liable to damage in shipment or handling. The light beams and photographic film used in recording also eliminate the inertia inherent in other methods of recording.

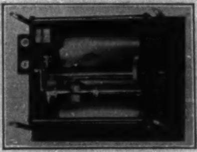
Fig. 9—Moving Film Mechanism for Single-Element Recorder

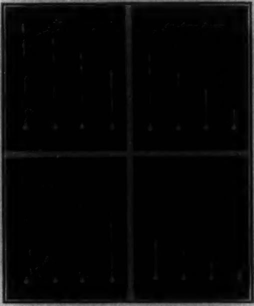
Fig. 10—Calibration Records Made With Single-Element Recorder

## OPERATION

As indicated earlier, the high-speed recorder begins operation automatically upon the occurrence of an overload, or fault. This is accomplished through a high-speed current-operated relay which is continuously connected in the neutral ground circuit. The high-speed relay for the four-element recorder is contained in a separate case (Fig. 3) while that for the single-element device is contained inside the case of the recorder proper.

In operating, the high-speed relay energizes three small contactors which connect the voltage elements to the line. The high-speed relay also turns on the recording lamp and releases a constant speed spring motor which rotates the plane mirror *F* of the four-element recorder or advances the film in the single-element recorder. At the end of the recording period a contact is opened by the spring motor which completely deenergizes the recorder control circuit, turning off the light source and disconnecting the recording elements. The operator, upon arrival, renews the film, rewinds the spring motor, and releases a latch in the high-speed relay. The recorder is then ready for operation again, and the exposed film is taken into a dark room for development.

## RECORDS

The size of record furnished by the four-element recorder is 11 in. by 14-in., and is made on standard film. The records made by the single-element recorder, stationary film type, are 3¼ in. by 4¼ in. and are also made on standard film. The single-element recorder for moving film uses standard 3¼ in. by 5½ in., 12-exposure Kodak film.

## SCALES

Standard deflection scales are as follows:

a. Four-element device
    70 volts per in.
    5 amperes per in.
b. Single element (ammeter)
    On 30 ampere coil —10 amperes per in.
    On 60 ampere coil*—20 amperes per in.

## TIME LAG OF RELAY AND LAMP

It is important that the time required for the high-speed relay to operate and for the lamp filament to reach recording brilliancy be very short, in order that the record may cover the complete disturbance. Tests have shown these time lags to be as follows:

a. Lag of High-Speed Relay on 60 Cycles

| Per cent of critical current | Time in sec. | Cycles at 60 ~ |
|---|---|---|
| 150 | 0.0058 | 0.348 |
| 200 | 0.0035 | 0.210 |
| 500 | 0.0020 | 0.120 |
| 1000 | 0.0012 | 0.072 |
| 2000 | 0.0010 | 0.060 |

b. Lag of Recording Lamp

| Lamp rating | Volts applied | Time in sec. for lamp to begin to record | Cycles at 60 ~ |
|---|---|---|---|
| 18-24 v., 27 cp. auto headlight. | 35.5 | 0.027 | 1.62 |

c. Total Time to Begin to Record
(Sum of lags of high-speed relay and lamp)

| Per cent of critical current | Time in sec. | Cycles at 60 ~ |
|---|---|---|
| 150 | 0.033 | 1.97 |
| 200 | 0.031 | 1.83 |
| 500 | 0.029 | 1.74 |
| 1000 | 0.028 | 1.69 |
| 2000 | 0.028 | 1.68 |

## MISCELLANEOUS APPLICATIONS

The possible applications of this type of instrument are numerous and varied. Figs. 11 and 12 show test records made using slight modifications of the standard recorder in order to give a time scale of 5 in. per sec. and also to add a timing indication to the chart. The latter was done by focusing the rays of a small high-speed filament hydrogen-filled lamp on the lower edge of the film. This lamp was operated by a 60-cycle supply circuit and thus produced on the record a row of timing dots 1/120 sec. apart.

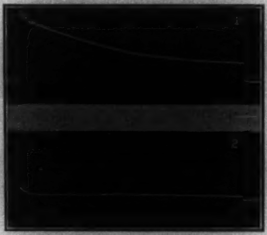

FIG. 11

1. 20-Ampere load applied to 1-kw., 150 volt, d-c. motor-generator set.
2. Starting current of 200-watt Mazda C lamp.

Chart 1, Fig. 11 shows the variation in current following the application of a 20-ampere load to a 150-volt d-c. line supplied by a small 1-kw. motor-generator set. The record shows how the current rose at once to a maximum value and then tapered down gradually, owing to a reduction in speed of the overloaded motor-generator. The detail of the record is exemplified by the small variations in the record line caused by sparking of brushes. The timing dots show that the complete interval during which the circuit was closed was 1.2 sec.

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*NOTE. The ammeter coil of the single-element recorder is equipped with taps so that if desired, only one-half of the winding may be used, thus doubling the current capacity of the instrument.

Chart 2, Fig. 11 shows the starting current of a 200-watt Mazda C lamp, indicating the initial rush of current with cold filament and the reduction in value as the filament becomes heated.

Fig. 12 shows the blowing of plug and cartridge fuses under various conditions on a 220-volt d-c. circuit. In each chart, ordinates represent current values and time reads from left to right. Chart 1 was made by a 6-ampere plug fuse connected in series with a 20-ampere resistance load. The fuse blew in approximately 0.75 sec. and the arc was extinguished quickly. Chart 2 was made by another plug fuse of the same rating and with the same current value, but using an inductive rather than a resistance load. It will be noted that in this case the current value builds up more gradually and that an arc continues for about 0.35 sec. after the fuse wire has melted.

Fig. 12—Blowing of Fuses on 220-Volt D-c. Circuit

1. 6-Ampere plug fuse on 20-ampere resistance load
2. Same as "1" except inductive load
3. 5-Ampere cartridge fuse on 20-ampere resistance load
4. Same as "3" except inductive load

Chart 3, Fig. 12 shows the blowing of a 5-ampere cartridge fuse on a 20-ampere resistance load. Chart 4 shows the same conditions except for the substitution of an inductive load. It will be noted that the cartridge fuse opened the inductive current without the formation of an arc.

Other suggested uses for the high-speed recorder include the investigation of starting currents of motors, motor current values on high overloads of short duration, brief reductions in line voltage due to starting of motors or other high-current loads, and general laboratory investigations where the device may be used for visual readings or permanent records.

## Discussion

### HALL HIGH-SPEED RECORDER

(Hall)

### PAGES FROM THE HALL HIGH-SPEED RECORDER[1]

(Tingley)

New Haven, Conn., May 9, 1928

**Alexander Dovjikov:** In an effort to overcome the slow response of ink-recording instruments, Mr. Hall devised the instrument described in his paper and in the paper by Mr. Tingley. This instrument is of the type intermediate between the ink-recorder and the oscillograph. By introducing the galvanometer and photographic method of recording, Mr. Hall eliminated to a certain degree the distorting features of the moving masses of the recorder although a small amount of overshooting may still be observed on the records.

The convenience of the Hall recorder in using the stationary plate instead of a rotating film as in the oscillograph is compensated by the fact that the former cannot record a second disturbance until the photographic plate is changed. Due to this limitation the instrument will require more attention and in certain cases the operation of the system, such as the reclosing of a breaker on a fault, cannot be recorded unless the time of a single operation of the recorder is unreasonably extended.

The statement of Mr. Tingley that "starting on neutral ground current is the best compromise that can be effected" may be true in application to Mr. Tingley's system for measuring of values he had in mind but is not generally true for all systems because this relay, functioning on ground current, will not operate in case of a phase-to-phase short circuit unless it develops into a fault to ground. We believe that a modified negative-sequence relay, which may be applied to grounded or ungrounded systems and will operate in the case of a ground fault as well as in the case of a phase-to-phase short, will be preferable in many cases.

**C. I. Hall:** Mr. Dovjikov mentions the moving masses of the recorder, as affecting the accuracy of the instrument. It should be understood that the recorder element has been so designed as to have a minimum of inertia and high restraining torque in the torsional rod carrying the vane. The angular twist of the recording vane is very small (about 1.2 deg. per in. of deflection on the film). In addition, the optical method of recording eliminates all inertia effects other than those originating in the galvanometer element. As the result of the foregoing features of design, overshooting of the recording element is small and is not sufficient to interfere with the commercial accuracy of the instrument.

The comment has also been made that the stationary film used in the recorder permits of recording only one disturbance without renewing the film. This is true of the four-element recorder only, as the single-element device is equipped with an automatic moving film mechanism which records four successive disturbances.

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[1] A. I. E. E. Quarterly Trans., Vol. 47, No. 1, Jan. 1928, p. 252.

# A High-Speed Graphic Voltmeter
# for Recording Magnitude and Duration of System Disturbances

BY A. F. HAMDI[1] and H. D. BRALEY[1]
Member, A. I. E. E. Associate, A. I. E. E.

***Synopsis.**—This paper deals with a graphic voltmeter for recording the magnitude and duration of system disturbances. It also deals with operating experiences with this device, together with the importance of the data obtained.*

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### INTRODUCTION

THE high-speed recording voltmeter described in this paper is one of a number of types now on the market which have been built in order to supply the needs for a type of instrument which would give an accurate record of system disturbances. It was felt that such instruments would be useful in determining actual magnitude and duration of disturbances and their relation to the operation of high-tension circuit breakers and relays on apparatus connected to the system.

The first part of this paper deals with the description of the electrical and mechanical details of this instrument, with particular reference to the requirements which were submitted to the manufacturers who developed the device. These requirements resulted from four years of operating experience with a similar type of instrument which accomplished the results desired. The second part of the paper deals with the interpretation of the records obtained and their value to the engineering and operating departments in analyzing system disturbances.

Several years ago the Engineering Department and Test Department of the New York Edison Company investigated the methods available for obtaining records of voltage dips during disturbances on power systems, and as a result an instrument was developed which consists of a high-grade graphic voltmeter driving a chart at normal speed and an auxiliary circular chart driven at relatively high speed. To the pen arm of the graphic voltmeter is attached a long pointer in addition to the standard pen of the instrument. This long pointer reaches over to a circular smoked chart which revolves at the rate of 2.5 rev. per min. (24 sec. per revolution). This circular chart is driven by a d-c. motor operating from the station control battery so that its speed is not influenced by the changes in system voltage. With this device it is possible to obtain records of both magnitude and duration of all disturbances. Two of these instruments have been in successful operation for four years and have given quite satisfactory results. The main objection to this device is that the smoked chart has to be renewed after each disturbance. It was therefore desired to obtain an instrument which would eliminate the above difficulty by giving the high-speed record on the standard strip chart.

From the operating experience obtained with the above instruments, certain specifications were drawn which were placed in the hands of instrument manufacturers and resulted in the development of the instrument described in this paper. With this device the high chart speed is 3600 times the normal chart speed and the change-over is accomplished in 0.05 sec. or less (1 to 3 cycles for 60-cycle systems).

The following characteristics were required:

1. A graphic voltmeter responsive to all voltage fluctuations, but well damped so as to be free from over- or under-shooting even for 100 per cent voltage fluctuations (suddenly energized to 115 volts or 115 volts suddenly interrupted).
2. Instrument to take 1.0 sec. or less to reach 115 volts when suddenly energized.
3. High-speed timing accuracy to be within 0.1 sec.
4. Chart acceleration time 3 cycles or less on 60-cycle systems (0.05 sec.).
5. Low-voltage relay capable of being set to function on a voltage dip of 5 per cent of normal or less.

FIG. 1—GENERAL VIEW OF A GRAPHIC SYSTEM—DISTURBANCE RECORDER

The manufacturers were left entirely free to work out all details.

### DESCRIPTION

The device described in this paper is illustrated in Fig. 1. It consists primarily of a standard type of graphic voltmeter *A*, a chart accelerator *B*, a contact-making voltmeter *C*, and the necessary resistors *D* and *E*. The wiring diagram of this device, together with

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[1] Assistant Engineer, The New York Edison Company, New York, N. Y.

*Presented at the Regional Meeting of the A. I. E. E., Northeastern Dist. No. 1, New Haven, Conn., May 9-12, 1928.*

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the schematic layout of the component parts, are shown in Fig. 2.

All the component parts of the above device are designed to operate at 115 volts, 60 cycles, with the exception of the magnetic clutch, which operates at 120 volts d-c. The contact-making voltmeter can be set to function at all dips in voltage amounting to two per cent of normal, or more. Actually, however, it is set to function at 5 per cent dips.

Under normal operating conditions the strip chart of the graphic voltmeter *A* runs at the normal speed of 3 in. per hr.; the salient-pole induction motor of the accelerator *B* runs continuously at synchronous speed; and the contact-making voltmeter *C* being energized at full voltage holds open its contact *V*. As soon as a dip in voltage occurs, amounting to five per cent of normal or more, the contact-making voltmeter closes its contact and energizes the magnetic clutch of the chart accelerator *B*. When the clutch engages, the chart accelerator motor runs the strip chart of the graphic voltmeter at the high speed of 3 in. per sec. The high speed continues even after the disturbance is over, for a length of chart equivalent to 24 hr., or 24 sec. in actual time. At the end of this time, a cam, which is operated by a worm gear, located on the magnetic clutch shaft, opens the circuit of the magnetic clutch at point *X* (see Figs. 1 and 2). If the voltage is back to normal, the slow chart speed is resumed as the contact-making voltmeter contact *V* would then be open. In case the voltage is still below normal, the contact-making voltmeter will have its contact *V* closed and the cam will keep the device running at high speed for an additional period of 24 sec. Normally the cam holds the contact at *X* open.

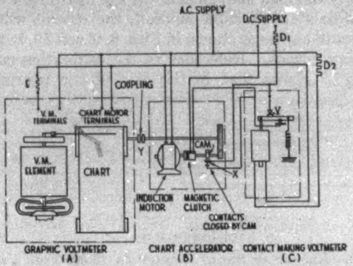

FIG. 2—SCHEMATIC LAYOUT AND WIRING DIAGRAM

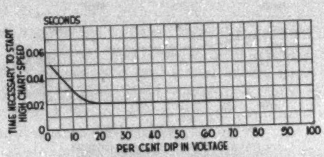

FIG. 3—STARTING TIME OF HIGH CHART SPEED

The time necessary for the accelerator to speed up the chart has been carefully investigated and was found to be dependent upon the magnitude of the voltage dips which affect the speed of operation of the contact-making voltmeter. For all dips amounting to more than 20 per cent of normal the device requires 0.02 sec., (1.2 cycles) to change over to the high speed. With dips less than 20 per cent, the change-over time may be as high as 0.05 sec. (3 cycles). The variation in this time is shown in Fig. 3.

The timing accuracy of the high-speed chart is correct within 0.1 sec. for the full length of the high speed run (72 in. length of chart) providing the dip does not exceed 50 per cent of normal. For greater dips in voltage, the accelerator motor slips and the timing error becomes greater. The curve in Fig. 4 shows the timing error during 24 sec. for voltage dips up to 70 per cent. For voltage dips beyond 70 per cent the driving motor stops if the disturbance is sustained. However, the motor requires about 5.5 sec. to come to rest even if the voltage fails completely. Fig. 5 shows the record of a 100 per cent dip lasting for 1.08 sec., where the magnitude was correctly recorded. The time was in error by 0.2 sec. It should be noted, however, that for 100 per cent dips lasting for more than one sec. the magnitude can be obtained directly from the chart even though the duration is not correctly recorded.

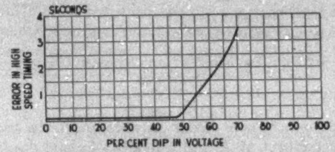

FIG. 4—TIMING ERROR IN 24 SEC. AT HIGH CHART SPEED

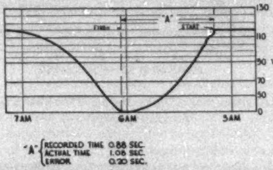

FIG. 5—TEST RECORD OF A COMPLETE VOLTAGE FAILURE

Voltage reestablished at the end of 1.08 sec.

To permit correct time resetting for slow speed after a disturbance, the high speed should last 24 sec., but actually it lasts only for about 23.96 sec. Therefore, there is a reset error in timing amounting to approximately 0.12 in. of chart length, which at slow speed means 2.5 min.

After the contact-making voltmeter operates to energize the magnetic clutch, 0.28 sec. is required for the cam to close the "hold-in" contact at *X* (see Fig. 2). Therefore, for disturbances having durations of less than 0.28 sec., the high speed lasts only as long as the disturbance, and the cam does not come into play. Fig. 6 shows such a short duration disturbance which was cleared in about 0.1 sec. However, if a number of short disturbances occur in succession, the cam will close the contact at *X* and a length of chart equivalent to 24 hr. will be run off as soon as the several short duration disturbances add up to 0.28 sec.

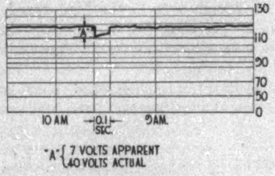

Fig. 6—Record of Momentary System Ground—Cause Unknown

In Fig. 7 is shown a set of calibration curves applying to this recorder. These curves have been prepared by subjecting the device to voltage dips of known magnitude and duration, and plotting voltage values obtained from the chart (ordinates) against time (abscissas). Normal voltage was 115 volts.

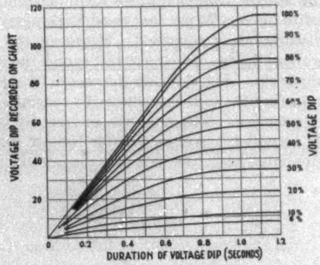

Fig. 7—Calibration Curves for Determining True Voltage Dip

The following procedure would be used to obtain the magnitude of a disturbance of known duration. From the high-speed section of the chart, obtain the apparent maximum dip in voltage and the duration of the disturbance. Plot the point corresponding to these two observations on the calibration curves. The true per cent voltage dip can then be obtained by comparing the position of the point so plotted to the calibration curves. As an example, if the apparent voltage dip were 40 volts, and the duration of the disturbance were 0.40 sec., we find by reference to Fig. 7 that the point determined by these two values falls very close to the 60 per cent dip curve. Therefore, we conclude that the actual dip was approximately 60 per cent of normal or 70 volts.

In connection with these calibration curves it should be pointed out that it is quite essential to have a properly damped instrument. If the instrument overshoots to a considerable amount, the records will not be smooth curves as shown in Figs. 8, 9, and 10, but will be wavy curves. Reference to the calibration curves in Fig. 7 shows that in the case of the instrument discussed, there is no overshooting and the instrument reaches full indication in about 1.1 sec. In other words, for disturbances lasting over 1.1 sec. there is no need for reference to the calibration curves, as the maximum dip recorded on the strip chart is the true dip.

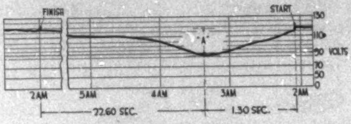

Fig. 8—Record of Short Circuit on 13,800-Volt Feeder

## OPERATING EXPERIENCE

Since this instrument was placed in service, on a 60-cycle cable system, 15 records of voltage disturbances were obtained. Most of these voltage dips were 20 per cent or less of normal voltage and the trouble was cleared from the system automatically in 1.5 sec. or less. While practically all of these faults show the same characteristics, there were a few cases of rather different nature which illustrate the adaptability of the instrument for this service. In the following figures the smooth voltage recovery sections have been cut off in order to shorten the length of the records. The broken lines show where chart sections have been cut off.

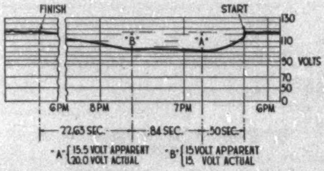

Fig. 9—Record of Short Circuit on 13,800-Volt Feeder

Fig. 8 is a typical record which is representative of the voltage disturbances resulting from faults on the system. This record shows a dip of 31 volts, or approximately 26 per cent, the disturbance being cleared by the opening of the circuit breakers after 1.3 sec. It may be noted that the duration of the disturbance is measured from the start to a point where the voltage begins to recover.

Fig. 9 illustrates a disturbance which lasted for 1.34 sec. before it was finally cleared. The first circuit breaker opened after 0.50 sec., while after an additional 0.84 sec. the second circuit breaker cleared the other end of the feeder. Since the first switch opened after but 0.5 sec. the instrument did not attain its maximum swing, the calibration curves showing the actual dip to be 20 volts instead of 15.5 as recorded. This curve also illustrates the manner in which it is often possible to obtain a check on relay operations, as two distinct circuit breaker operations are indicated.

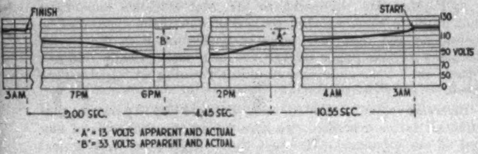

Fig. 10—Record of Ground and Short Circuit on 27,000-Volt Feeder

Fig. 10 is an unusual case in that the disturbance lasted for approximately 15 sec. before it was finally cleared. In this case a triplex cable became grounded at a considerable distance from the supply end and was not cleared immediately because the moderate ground current was insufficient to cause the overload relays to operate. The voltage dip due to the ground was approximately 11 per cent and lasted about 10.55 sec. Apparently the ground then developed into phase trouble causing a dip of about 28 per cent and was finally cleared after an additional 4.45 sec.

In each of the above cases the records show that a considerable length of time is required for the voltage to return to normal. Of this time, one sec. is due to time lag in the instrument if the dip is 100 per cent. If the dip is less than 100 per cent, the time lag of the instrument will be correspondingly reduced.

Fig. 6 illustrates a case in which a momentary ground occurred which apparently cleared itself in about 0.1 sec. The contact of the contact-making voltmeter opened before the cam could operate the hold-in contact to continue the high-speed operation.

While an instrument of this nature will not record instantaneous changes in voltage or current, it does afford a means of giving directly a fairly accurate picture of the disturbance even though it may last several minutes. All disturbances are recorded by this instrument even if they last more than 24 sec. because the instrument will operate continuously through successive periods of 24 sec. as long as the contact-making voltmeter contact is closed. An instrument designed to operate on current instead of voltage, for example, would give a record of surging between generating stations due to a condition of instability which might last for several minutes. Such an instrument may also be installed at grounding points to indicate the magnitude and duration of ground fault currents as a check on the effectiveness of the grounding itself and for checking relay operations.

The results obtained with the device described have been quite satisfactory from both the operating and the maintenance standpoints. The records obtained have given sufficiently accurate information in regard to the magnitude of voltage dips and their relation to operation of low-voltage relays. These records have an additional value in that they often afford a means of checking automatic circuit breaker operations and also give a fairly accurate indication of the effect of faults on the system in general.

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## Discussion

**J. E. McCormack:** (communicated after adjournment) We have had some experience with an instrument similar in construction to the one described by Messrs. Hamdi and Braley in their paper.

We have experienced considerable difficulty in maintaining an accurate calibration on this instrument. The graphic voltmeter is equipped with an oil dash pot to damp the meter and prevent overswinging on a dip. The calibration of the meter depends almost entirely on the amount and viscosity of the oil in the damping chamber, and changes in temperature, or evaporation or leakage of the oil, will throw the calibration off.

We have also found that the slip of the induction motor driving the high-speed device is sufficient to cause a discrepancy in time as high as fifteen or twenty minutes on each high-speed run. This discrepancy varies with the amount and duration of the dip in voltage.

In respect to the electrical location of the disturbance recorder in the station, we have found that the only satisfactory method of connection is on one phase of one feeder or bus section. An attempt was made to connect a recorder to six 13,200-volt feeders on two sections of a bus, but the voltage difference between the two sections was sufficient to keep the chart running continually at high speed. Any method of connection to one feeder or bus with automatic throw-over to the other when the first is taken out of service is inherently wrong since the throw-over switch causes an indication of a dip at every operation. Also, a heavy dip is likely to cause the throwover relay to operate and makes an analysis of the dip impossible.

**D. J. Angus:** (communicated after adjournment) The desirability of speeding up the chart of graphic meters when important records are to be obtained was recognized about fifteen years ago, when the company with which the writer is connected was called upon to furnish graphic recording pressure gages for use in air-brake testing. These gages were provided with a pressure-controlled mechanism which speeded the chart up from three in. per hour to three in. per minute when any abnormal operation took place, and returned the speed to three in. per hour after this condition had passed.

Later, when public utilities felt the need for an instrument of this kind, it was found necessary to continue the rapid speed of the chart after the trouble ceased, until the chart came to the same time marking, 24 hours later on the chart, before resuming the slow chart speed, in order that a number of records could be secured in succession, without any attention on the part of the operator. Mr. Hamdi mentioned the cam-operated holding-in device, which requires approximately 0.28 seconds before it becomes operative. My experience has been that the holding-in device must operate the instant the high-speed drive comes into play, because if it does not, the circuit to which the tripping mechanism is connected may be disconnected by the automatic oil switches or other protective devices, and no high-speed records secured of the trouble and the recovery after the disturbance. Often this recovery will take several minutes, and a complete record of it is of utmost importance.

Instruments which the writer has designed for power-plant service are equipped with a double cam arrangement such that the first momentary impulse locks it in the high-speed position, where it remains until at least 24 hr. of chart (24 sec.) has been passed.

In the next to the last paragraph of Mr. Hamdi's paper, he mentions that an instrument designed to operate on current instead of voltage would give a record of surging between generating stations due to a condition of instability which might last for several minutes. We have actual records from large generating stations connected by tie lines operating out of synchronism for over four minutes, and numerous records where the system did not steady down to normal operation until after a minute had elapsed.

In addition to recording voltage and current in times of trouble, instruments equipped with the high-speed chart mechanism have for a number of years been used to record the power factor or phase position of the current in reference to the voltage in the generator leads and tie lines, the power transfer in kilowatts, kv-a. pressures surges in pipe line feeding hydraulic turbines, speed changes in prime movers, and pressure or other mechanical records of the functioning of governing equipment.

High-speed graphic recording instruments are long past the experimental stage, and hundreds of them are in use securing a wide variety of data on the operation of the various pieces of equipment that make up a modern power generating and distributing system.

**A. F. Hamdi:** Referring to Mr. McCormack's remarks, I should like to point out that we had predicted the difficulties he mentioned and that they have been eliminated in the device discussed in this paper by the use of a magnetically damped "dead-beat" voltmeter and a motor running at synchronous speed.

Referring to Mr. Angus' remarks, I should like to point out that with the device described, we obtain high-speed records of any and all disturbances. The fact that disturbances lasting less than 0.28 sec. do not result in a complete 24-hour run at high speed is of no particular importance, because usually such disturbances are of no serious consequence and they clear themselves as discussed in connection with Fig. 6 of the paper.

Particularly in view of the facts brought out by Mr. McCormack, I have to take exception to Mr. Angus' statement and hold the view that although hundreds of such devices are in use, they are still more or less in the experimental stage.

# Selection of Motor Equipment by Principle of
## Similar Speed-Time Curves

BY BERNDT A. WIDELL, JR.[1]

Member, A. I. E. E.

***Synopsis.**—Data for making preliminary estimates of speed of cars required and capacity of motor to do a given service have been rather limited. The object of this paper is to show a method whereby it is possible to provide curves which are simple to calculate and easy to apply.*

*No mathematical formula has ever been derived to express the speed-time or current-time curves for a railway motor. Similarity between speed-time curves has been resorted to and this paper shows how this method can be used to give very accurate results by proper consideration of the various factors which influence the shape of the speed-time curve.*

*Previous methods for estimating motor capacities are based on the horsepower of motor required, but with the advent of the self-ventilated and blown motors it is necessary to calculate the r. m. s. current for a given cycle and select a motor having this continuous rating. A method for doing this is proposed, based on similar current-time curves.*

*The limiting values of average running speeds for given rates of acceleration and braking, and the data for obtaining motor capacity necessary at these limits are indicated on each curve. This helps one to visualize why it is not practicable to perform certain schedules on a fixed rate of acceleration and braking basis.*

ONE of the most complicated engineering problems is that of selecting the proper motor equipment to perform a given railway service. By "service" we mean that cars must make a given number of stops and slowdowns over a route in a given time. In many instances the profile of the route is hilly, and voltage varies on different sections of the route, thus making it necessary to consider small sections of road at a time in our calculations to arrive at a suitable motor equipment. Unless one has had considerable experience in the application of motors to different services, it may require weeks of calculation to determine on the motor equipment of required speed to do the service with the least energy consumption and a conservative motor capacity. As a first approximation it is usually assumed that the route is absolutely level. An average line voltage is also assumed, thereby reducing the work to a few simple speed-time curves. In the majority of cases, such a solution is accurate enough, but if it is not, sufficient information has been obtained to shorten the work of making detailed calculations over the entire profile as it actually exists and for the varying line voltages. Even with this simplification, considerable calculation may be necessary before the proper speed equipment is determined, or it is found that an uneconomical or impossible schedule has been requested.

Several electric railway engineers (among them, E. H. Anderson, A. H. Armstrong, and F. W. Carter) have plotted curves from which a rough approximation of the speed of equipment necessary to do a certain service can be made. These curves have been prepared for a very limited group of conditions for which they give accurate data. They can also be used, however, as a rough approximation for other conditions, but realizing that much more accurate curves could be plotted to cover greater ground, an investigation was made which showed that the car friction and slope of the motor speed-tractive effort curve were the factors which most influenced the shape of the speed-time curve, and hence the schedule speed, for a given rate of braking and acceleration. Referring to Fig. 1, curves *B* and *C* are speed-time curves for a certain weight of car, making the same scheduled speed for the same length of run. The speed on leaving control and free running speed are shown in the table. It should be noted that for the same value of car friction there is a 5.5 per cent difference between speeds on leaving control, and 7 per cent difference between free running speeds, due to different motor characteristics alone. Comparing curve *C* with *A*, the difference between speeds on leaving control and free running speeds is 15 per cent and 19 per cent respectively. Obviously, if we are to make up curves that are to possess any degree of accuracy, the car friction and slope of speed—tractive effort curve must be considered.

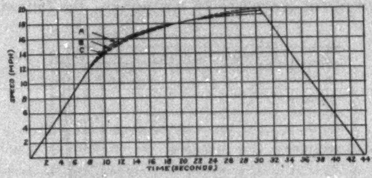

FIG. 1—SPEED—TIME CURVES ILLUSTRATING THE DIFFERENCES IN SHAPE DUE TO THE SLOPE OF SPEED TRACTIVE EFFORT CURVE AND THE CAR FRICTION

A—Average motor characteristic, friction 40 lb. per ton
B—Flat motor characteristic, friction 20 lb. per ton
C—Steep motor characteristic, friction 20 lb. per ton
Speed on leaving control (mi. per hr.) A—12.9, B—11.8, C—11.2
Free running speed (mi. per hr.) A—20.1, B—22.3, C—23.9

Conditions: Length of run 830 ft., rate of acceleration and braking 1.5 mi. per hr. per sec. Average running speed 12.96 mi. per hr. Constant car friction

First let us consider the effect of the slope of motor

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characteristic on the schedule speed. In order to distinguish between two different motor characteristics, the one whose speed tractive effort curve has the greatest slope is termed steep, whereas that with the less slope is flat. Fig. 2 illustrates the difference in the two motors' characteristics. Referring to Fig. 3 and assuming the number of stops per mile being made as one, we can read the free running speed corresponding to the average running speed directly. With an equipment geared to 75 mi. per hr., the following average running speeds can be made with a motor having the steepest and flattest characteristic respectively 34.6 mi. per hr. and 35.3 mi. per hr., a difference of 2 per cent. With a 35-mi. per hr. equipment, the difference in average running speed is 1 per cent, and with an equipment of 30 mi. per hr., an average running speed of 24 mi. per hr. is obtained with either slope of characteristic. Over the usable part of this curve, the maximum variation in average running speed due to the slope of motor characteristic is 2 per cent. If we base the curves on an average motor characteristic as indicated, the maximum variation in average running speed from either steep or flat characteristic is about 1.4 per cent.

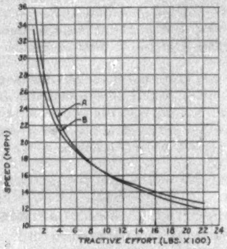

FIG. 2—SPEED—TRACTIVE EFFORT CURVE OF TWO MOTORS HAVING A DIFFERENCE IN SLOPE

A—Steep motor characteristic
B—Flat motor characteristic

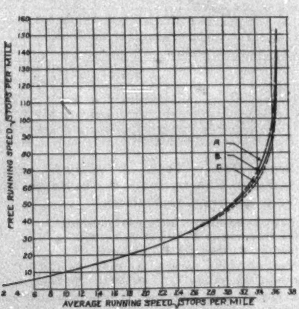

FIG. 3—CURVES ILLUSTRATING THE DIFFERENT FREE RUNNING SPEEDS REQUIRED FOR MOTORS HAVING DIFFERENT SLOPE SPEED—TRACTIVE EFFORT CURVES

Conditions: Rate of acceleration and braking 1.5 mi. per hr. per sec. Constant car friction 20 lb. per ton. No coasting, no leeway

A—Steep motor characteristic
B—Average motor characteristic
C—Flat motor characteristic

Next let us consider the effect of car friction on the average running speed. Referring to Fig. 4, a series of curves has been plotted using an average motor characteristic as determined in the above paragraphs. With a 75-mi. per hr. equipment, the average running speeds that can be made with car friction of 10, 20, 30, and 40 lb. per ton are respectively 33.6, 35.0, 35.5, and 36.0 mi. per hr. The per cent differences in average running speeds are respectively 4.2, 1.5, and 1.3. Practically all other curves of a similar nature have been based on 20 lb. per ton friction; hence, the error where the actual friction is 10 lb. per ton is 4.2 per cent, for 30 lb. per ton friction 1.5 per cent, and for 40 lb. per ton friction 2.8 per cent. We can eliminate this error by using the average motor characteristic and plotting curves for the various friction values encountered, in which case the maximum error in average running speed calculated from these curves should not exceed 1.4 per cent.

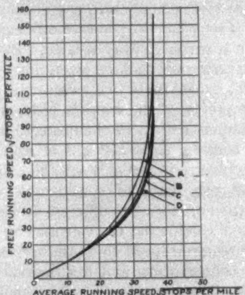

FIG. 4—CURVES ILLUSTRATING THE DIFFERENT FREE RUNNING SPEEDS REQUIRED WITH A MOTOR HAVING AN AVERAGE SLOPE SPEED—TRACTIVE EFFORT CURVE FOR VARIOUS CAR FRICTION VALUES

Conditions: Rate of acceleration and braking 1.5 mi. per hr. per sec. No coasting, no leeway, car friction constant at values given

A—10 lb. per ton car friction, B—20, C—30, D—40

Use: Abscissas are the values of average running speed times $\sqrt{\text{stops per mile}}$, and corresponding values of ordinate on friction curve divided by the $\sqrt{\text{stops per mile}}$ gives the free running speeds necessary to make the average running speed

The method by which curves of Fig. 3 and Fig. 4 were calculated is a development of the similar speed–time curve idea. For instance, if speed–time curves are calculated, using the average characteristic and a given rate of acceleration and braking for different lengths of run, a series of different shaped speed-time curves is obtained. The shortest run will be represented by a triangle, a slightly longer run will show the car accelerating according to the slope of motor characteristic and value of car friction and the longest run will be practically at free running speed. If a means is obtained for expressing each of these speed-time curves in terms of similar speed-time curves to give greater or less distance traversed, it will be possible to represent every existing running condition. How this is accomplished can be best explained by referring to Fig. 5.

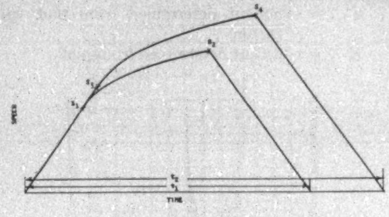

FIG. 5—SIMILAR SPEED—TIME CURVES

Let $D_1$ = distance traveled in $t_1$ seconds.

$D_2$ = distance traveled in $t_2$ seconds.

On an assumption that the two curves are similar, the following relations are true.

$$\frac{D_1}{D_2} = \left(\frac{S_1}{S_3}\right)^2 = \left(\frac{t_1}{t_2}\right)^2 = \left(\frac{V_1}{V_2}\right)^2 = \left(\frac{S_2}{S_4}\right)^2$$

where $V_1 = \frac{D_1}{t_1}$ and $V_2 = \frac{D_2}{t_2}$ = average running speed

or since $D_1 = \frac{5280}{\text{stops per mile}_1}$ and $D_2 = \frac{5280}{\text{stops per mile}_2}$

we can write $\frac{\text{stops per mile}_2}{\text{stops per mile}_1} = \left(\frac{S_1}{S_3}\right)^2 = \left(\frac{t_1}{t_2}\right)^2$

$$= \left(\frac{V_1}{V_2}\right)^2 = \left(\frac{S_2}{S_4}\right)^2$$

And by transposition, using an abreviation of stop per mile $S/M$,

$$\underline{S/M_1}\ S_1^2 = \underline{S/M_2}\ S_3^2$$

or $$\sqrt{S/M_1}\ S_1 = \sqrt{S/M_2}\ S_3 \quad (1)$$

and similarly $$\sqrt{S/M_1}\ V_1 = \sqrt{S/M_2}\ V_2 \quad (2)$$

$$\sqrt{S/M_1}\ t_1 = \sqrt{S/M_2}\ t_2 \quad (3)$$

$$\sqrt{S/M_1}\ S_2 = \sqrt{S/M_2}\ S_4 \quad (4)$$

Referring back to the different shaped speed-time curves, we can calculate $\sqrt{S/M_1}\ S_1$ and $\sqrt{S/M_1}\ V_1$ for each speed-time curve and plot a curve of (average running speed) × $\sqrt{\text{stops per mile}}$ against (speed on leaving control) × $\sqrt{\text{stops per mile}}$. Equations (**1**) and (**2**). $S_1$ of Fig. 6 shows such a curve based on the average characteristic. The value of $S_1$ is the product of (speed on leaving control) × $\sqrt{\text{stops per mile}}$. There is also shown a $S_2$ curve, the value of $S_2$ being (speed at which braking starts) × $\sqrt{\text{stops per mile}}$. Equation (**4**).

Thus, knowing the schedule speed required and the average length of run, the speed on leaving control can be calculated from Fig. 6 and a motor selected with a gear ratio such that it will have this speed at the tractive effort necessary to accelerate the car at the desired rate and at the average line voltage. However, this curve (Fig. 6) is not applicable to the tapped field motor because the speed on leaving control resistance points is quite different for a tapped and full field motor when

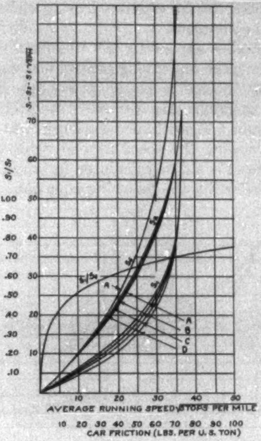

FIG. 6—CURVES FOR ESTIMATING SPEED AT END OF ACCELERATION, SPEED AT INSTANT OF BRAKING AND FREE RUNNING SPEED

$S_1$—Speed at end of acceleration times $\sqrt{\text{stops per mile}}$
$S_1/S_f$—Ratio of speed at end of acceleration to free running speed
$S_2$—Speed at which braking commences times $\sqrt{\text{stops per mile}}$
$S_f$—Free running speed times $\sqrt{\text{stops per mile}}$

A—10 lb. per ton car friction
B—20 lb. per ton car friction
C—30 lb. per ton car friction
D—40 lb. per ton car friction

Conditions: Rates of acceleration and braking 1.5 mi. per hr. per sec. No coasting, no leeway, car friction constant at values given

Use: For a given value of abscissas; the free running speed is equal to value of ordinate $S_1$ divided by the value of ordinate $S_1/S_f$ for proper car friction value and by $\sqrt{\text{stops per mile}}$, or to the value of ordinate $S_f$ divided by the $\sqrt{\text{stops per mile}}$; the speed at instant of braking is the value of ordinate $S_2$ divided by the $\sqrt{\text{stops per mile}}$

both motors are geared to make the same free running speed. In view of the fact that a tapped field motor will make practically the same schedule speed as a full field motor, each having the same free running speed, and also to the fact that the free running speed of a full field motor can be expressed accurately in terms of the speed on leaving control, a more practicable set of curves has been calculated showing the relation between (average running speed) $\sqrt{\text{stops}}$ per mile and (free running speed) $\sqrt{\text{stops}}$ per mile. From these curves the free running speed necessary to make a given schedule speed can be estimated using either a full or tapped field equipment.

The method of expressing the free running speed in terms of the speed on leaving control was suggested by Mr. E. E. Kimball's paper presented before the A. I. E. E. in 1908. Mr. Kimball noted that the tractive effort had a logarithmic relationship to speed and therefore knowing the speed at one value of tractive effort the speed could be calculated for any other value of tractive effort by the following equation.

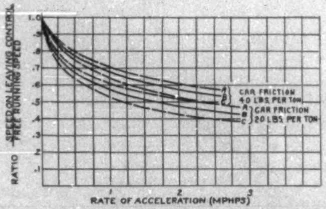

FIG. 7—CURVES ILLUSTRATING CHANGE IN RATIO OF SPEED ON LEAVING CONTROL TO FREE RUNNING SPEED WITH VARIOUS VALUES OF ACCELERATING RATES, CAR FRICTION, AND SLOPE OF MOTOR SPEED TRACTIVE EFFORT CURVES

A—Flat motor characteristic
B—Average motor characteristic
C—Steep motor characteristic

Formula $\frac{S_1}{S_f} = \sqrt[A]{\frac{p}{P}}$

Where $S_f$ = Free running speed mi. per hr.
$S_1$ = Speed on leaving control mi. per hr.
$A$ = Exponent expressing relationship between tractive effort and speed of motor characteristic
$p$ = Car friction at free running speed (lb. per ton)
$P$ = Tractive effort required to accelerate car at a given rate (lb. per ton)

$$S = S_0 \sqrt[3]{\frac{P_0}{P}} \qquad (5)$$

Where $S$ = speed at tractive effort $P$
$S_0$ = speed at tractive effort $P_0$

The cube root factor in Equation (**5**) represents the slope of the speed—tractive effort curve and as stated by Mr. Kimball was selected because of the ease of making certain calculations. The variation in this slope factor was determined by plotting speed against tractive effort on logarithmic paper for several motors varying in capacity. In the majority of cases the resultant curves were perfectly straight throughout the range of voltage and current that the motors would be normally used. Therefore, the logarithmic relationship between speed and tractive effort can be expressed by the following equation.

$$T\,E \times S^a = K \qquad (6)$$

where $T\,E$ = tractive effort (lb.)
$S$ = speed mi. per hr.
$a$ = exponent determined from plot (slope factor)
$K$ = constant determined from plot

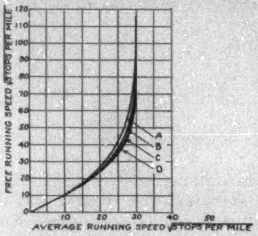

FIG. 8—CURVES FOR ESTIMATING FREE RUNNING SPEEDS

Conditions: Rate of acceleration and braking 1.0 mi. per hr. per sec. No coasting, no leeway, car friction constant for values given

Use: Abscissas are the values of average running speed times √ stops per mile and corresponding values of ordinate on friction curve divided by the √ stops per mile gives the free running speed necessary to make the average running speed

A—10 lb. per ton friction, B—20, C—30, D—40

The values of (a) varied between 2.8 and 3.5 representing, respectively, the steepest and flattest motor characteristics. A motor charcteristic having a slope factor of 3.2 represents the average slope of all motors considered and is that used as a basis of these curves.

Equation (**5**) shows that the ratio of speed on leaving control to free running speed depends on the slope of speed tractive effort curve, the car friction, and the rate of acceleration. Fig. 7 shows the variation of this ratio according to Equation (**5**). It is evident that with a given set of conditions the free running speed is a simple ratio of the speed on leaving control.

A set of curves based on different rates of acceleration and braking encountered in normal train operation, of (average running speed) $\sqrt{\text{stops}}$ per mile against (free running speed) $\sqrt{\text{stops}}$ per mile gives a ready means for determining the rates of acceleration and braking required and the free running speed necessary with those rates to make a given average running speed. Figs. 4, 8, and 9 show the character of such curves covering normal street car conditions.

As an illustrative example, suppose it is required to make a 37.5 mi. per hr. average running speed over average runs one mile long. By inspection of curves such speed cannot be made with 1 or 1.5 mi. per hr. per sec. accelerating and braking rates but with a 2.0 mi. per hr. per sec. rate of acceleration and braking a free running speed of 64 mi. per hr. per sec. is necessary assuming car friction at 20 lb. per ton. With this speed equipment it would be impossible to maintain an average running speed of 37.5 mi. per hr. over the usual roads due to traffic conditions and the fact that some coasting must occur. We shall, therefore, assume that an equipment to give a 5 per cent faster average running speed will take care of these delays. Our equipment must then be able to make 39.4 mi. per hr. average running speed when pushed to the limit and have a free running speed of 73 mi. per hr., according to Fig. 9, assuming car friction has increased to 25 lb. per ton.

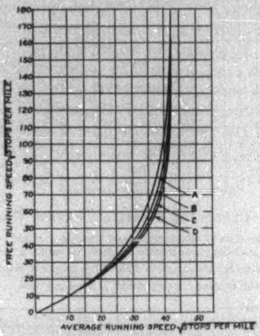

Fig. 9—Curves for Estimating Free Running Speeds

Conditions: Rate of acceleration and braking 2.0 mi. per hr. per sec. No coasting, no leeway, car friction constant for values given

A—10 lb. per ton car friction, B—20, C—30, D—40

Use: Abscissas are the values of average running speed times √ stops per mile and corresponding values of ordinate on friction curve divided by the √ stops per mile gives the free running speed necessary to make the average running speed

The curves as plotted were calculated on the assumption of a constant value of car friction from start to stop and are therefore only strictly accurate in the case where a car ascends a grade with no car friction. It is possible to plot the curves of free running speeds, r. m. s. current, and energy consumption using variable friction, but to do this involves the necessity of selecting an average friction curve. An examination of the many curves on car friction reveals not only a wide variation in friction values for the same car construction and weight, but also the ratio of car friction at end of accelerating period to that at the free running speed varies approximately as follows.

| | |
|---|---|
| Single motor cars | 0.55 to 0.40 |
| Multiple unit cars | 0.75 to 0.65 |

It is questionable, therefore, whether a single set of curves based on some average conditions of variable car friction would enable more accurate estimates to be made than using flat friction values.

The curves as calculated for constant friction values give results on the side of safety regarding free running speed, r. m. s. current, and energy consumption, if the actual car friction at free running speed is used. If values of r. m. s. current per ton and energy consumption are estimated on basis of car friction for speed at instant of braking, which is found from Fig. 4 curve $S_2$, a very close estimate of these values can be had.

By a similar manner in which the free running speeds have been obtained, the r. m. s. current can be estimated. Referring to Fig. 10, a series of curves gives the values of $A$ corresponding to the (average running speed) times $\sqrt{\text{stops per mile}}$. This factor is the actual value of (r. m. s. current per ton) times $\sqrt{\text{stops per mile}}$. The value r. m. s. current per motor as determined from curves must be either increased or decreased according to the average line voltage in question according to its variation from 600 volts on which the curves are based. The actual continuous rating of motor required is decreased from that estimated from curves when considering the duration of stop by the following relation.

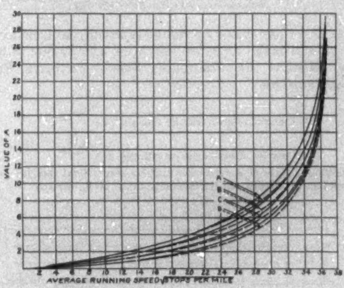

Fig. 10—Curves for Estimating Root-Mean-Square Currents for Specified Number of Stops per Mile and Schedule Speed

——————— Full field motor

- - - - - - - - Motor operating with 100 per cent & 60 per cent field

Conditions: Rate of acceleration and braking 1.5 mi. per hr. per sec. No coasting, no leeway

Use: Obtain value of ordinate $A$ on curve of car friction corresponding to average running speed $\sqrt{\text{stops per mile}}$ and apply in following formula

$$\text{R. m. s. current} = \sqrt{\left[\frac{\text{Value of } A}{\sqrt{\text{stops per mile}}} \times T \times \frac{600}{V}\right]^2 \left[\frac{t_1}{t_1\, t_s}\right]}$$

Where $T$ = tons per motor
$V$ = average line voltage
$t_1$ = time to make run excluding duration of stop (sec.)
$t_s$ = duration of stop (sec.)

A—40 lb. per ton friction
B—30 lb. per ton friction
C—20 lb. per ton friction
D—10 lb. per ton friction

$$I_1 = \sqrt{I_0^2\left(\frac{t_1}{t_1 + t_s}\right)} \qquad (7)$$

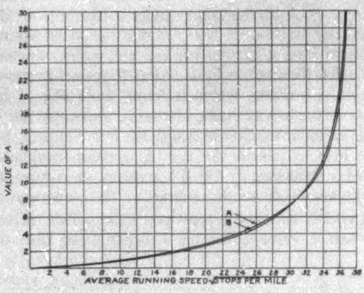

Fig. 11—Comparison of Root-Mean-Square Current for Specified Number of Stops per Mile and Schedule Speed With Motors of Different Speed—Tractive Effort Characteristics

A—Tractive effort varies as (mi. per hr.)$^{-\frac{1}{3.52}}$

B—Tractive effort varies as (mi. per hr.)$^{-\frac{1}{2.88}}$

Conditions: Rate of acceleration and braking 1.5 mi. per hr. per sec. No coasting, no leeway, car friction constant at 20 lb. per ton

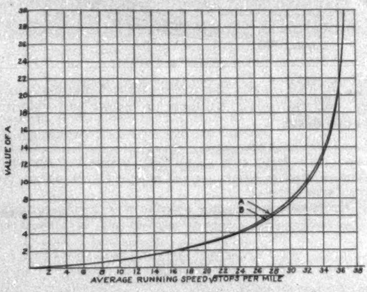

Fig. 12—Comparison of Root-Mean-Square Current for Specified Number of Stops per Mile and Schedule Speed With Motors of Different Speed—Tractive Effort Characteristics

A—Tractive effort varies as (mi. per hr.)$^{-\frac{1}{3.33}}$

B—Tractive effort varies as (mi. per hr.)$^{-\frac{1}{2.79}}$

Conditions: Rate of acceleration and braking 1.5 mi. per hr. per sec. No coasting, no leeway, car friction constant at 20 lbs. per ton

Where $I_1$ = r. m. s. current including time of stop
$I_0$ = r. m. s. current excluding time of stop (value obtained from curves)
$t_1$ = time to make run excluding stop (sec.)
$t_s$ = duration of stop (sec.)

An interesting comparison of the current required for a steep and flat motor characteristic can be made as shown on Figs. 11 and 12. This first curve is based on two motors having considerable differences in efficiency and shows that the steep characteristic motor demands less continuous capacity to perform a given schedule up to 30.9 than the motor with flat characteristic, but for greater values than 30.9 the condition reverses. Fig. 12 shows two motors having practically the same efficiency and favors the steep motor characteristic.

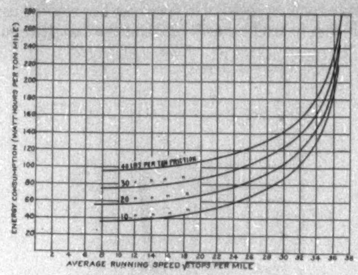

Fig. 13—Curves for Estimating Energy Consumption

Conditions: Rate of acceleration and braking 1.5 mi. per hr. per sec. No coasting, no leeway, car friction constant for values given

Use: Read energy consumption direct from proper friction curve corresponding to the average running speed √ stops per mile

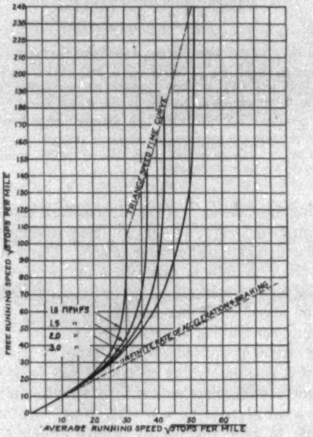

Fig. 14—Curves for Estimating the Increase in Average Running Speed With a Given Free Running Speed for Different Rates of Acceleration and Braking

Conditions: No coasting, no leeway, car friction constant at 20 lb. per ton

The curves of energy consumption on Fig. 13 are useful in determining the maximum energy consumption for a given schedule but as in case of the curves on r. m. s. currents they will not give accurate estimates unless a prediction can be made of the efficiency of the motor that will perform the service required.

The importance of making the best possible approximation of car friction is apparent on inspection of Figs. 10 and 13 for curves of r. m. s. currents and energy consumption, respectively. For example, assuming runs of one mile average length and an average running speed of 30 mi. per hr. the r. m. s. current per ton according to Fig. 10 is 7.4 for car friction of 20 lb. per ton and 6.3 for friction of 10 lb. per ton; a difference of 17.5 per cent. The energy consumption under same conditions is 105 watthour per ton mile for 20 lb. per ton car friction and 88 watthour per ton mile for 10 lb. per ton car friction; a difference of 19.2 per cent.

The greatest differences in average running speeds are those due to changes in the rates of acceleration and braking for cars having the same free running speeds. Fig. 14 shows these differences for rates between 1 and 3 mi. per hour per sec. It would appear from these curves that the highest rates would be the most advantageous, but we are limited to following considerations: first, comfort to passengers; second, in city service where high rates are desirable motors must be of light weight with small wheel diameters. This precludes use of large gear reduction or slow-speed motors with the present type of motor arrangement. Recent developments in the way of double reduction gearing and worm drive motors giving twice the normal reduction, permit the use of the higher rates of acceleration which Fig. 14 shows is desirable as it follows that with a lower free running speed, the motor capacity necessary is also less to perform a given service.

# Shunting of Track Circuit in a Polyphase System of Continuous Inductive Train Control

BY C. F. ESTWICK[1]
Member, A. I. E. E.

***Synopsis.**—Investigations into shunting of train control track circuits have been made in the field under operating conditions by observing the operation of the primary relay on a locomotive as a train runs into a track circuit in which there is a train ahead or an open switch and similar data have been obtained on the performance of the relay on trains in regular service.*

*It is intended in this paper to present a method for predetermining the shunting characteristics of train control track circuits. The system discussed is a polyphase system of continuous inductive train control with cab signals employed on double tracked steam roads. Curves are given which describe shunting conditions in train control track circuits and data are also given for comparison describing the shunting of the track relay on the same sections of track.*

IN a system of continuous inductive train control the apparatus on the trains on a steam operated railroad is located on the locomotive or tender and consists of a receiving system, visual cab signals, a train controlling mechanism that operates in connection with the automatic air brake equipment on the train, and auxiliary apparatus which include an acknowledging contactor and audible signals. The train controlling mechanism limits the speed of the train at all times to certain predetermined speeds which depend upon traffic conditions and the distance a train has traveled in a block. A failure on the part of the engineman to control the speed of the train properly results in an automatic application of the brakes as soon as the maximum allowable speed has been exceeded. After an automatic application has been made the brakes cannot be released until the speed of the train has been reduced below the maximum speed. When a train is traveling on clear track a clear signal indication is given in the cab and the speed of the train is limited to a safe speed which in the case of a passenger train may be 70 mi. per hr.; when the train enters a caution block the cab signal changes giving a caution or medium speed indication and the automatic controlling mechanism operates to enforce a gradual reduction in speed until the speed has been reduced to below 20 mi. per hr. at the exit end of the block. As a train passes from a caution into an occupied block the signal changes to a danger or slow-speed indication and the limitation of 20 mi. per hr. is maintained as long as the block is occupied by a train ahead.

The cab signals and speed controling mechanism are under the control of a three position a-c. primary relay. When the train is traveling under clear conditions the relay is in its normally energized position; when the train passes into a caution block the relay operates to the reverse position and when it is in an occupied block or a block in which there is an open switch the relay assumes its deenergized position and releases the normal or reverse contacts. The primary relay is under the control of an influence obtained inductively, by means of receivers on the locomotive, from alternating current flowing in the rails of the track.

The apparatus along the track includes the usual a-c. track circuit, modified slightly for train control purposes, and upon this is superimposed a so-called "line circuit." The actual current flowing in the rails consists of two components of current, one due to a voltage impressed on the circuit from the track circuit transformer and the other is due to voltage from a transformer in the line circuit. These two components of currents will be considered separately and will be referred to hereafter simply as "track circuit current" and "line circuit current." The wayside circuits are shown schematically in the diagram in Fig. 1 and may be traced as follows:—Track circuit current flows from the track circuit transformer which is located at the exit end of the block through a limiting impedance and a pole changer to one of the rails of the track, along the rail to the opposite end of the block through a variable resistance unit and windings of the track relay to the other rail, back along the rail and through the pole changer to the transformer. The relay is normally energized by current flowing in the track and local windings as shown in the diagram; the track windings receive current from the rails and the local windings

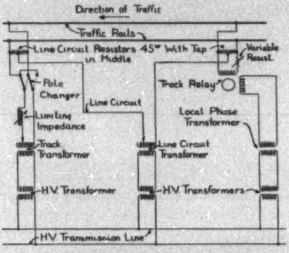

FIG. 1—TRAIN CONTROL TRACK CIRCUIT

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are energized by current from the local phase transformer. The track relay is the usual a-c. rotor type relay employed in railroad signaling which operates in three positions and requires the use of the pole changer in the track circuit to give normal and reverse operation. The normal and reverse control also permits of three position operation of the primary relay which is a similar two element relay of the rotor type. When a block is occupied by a train the current in the rails flows from one rail to the other through the wheels and axles of the train and on account of the very low impedance of the path through the wheels and axles most of the current is shunted from the track relay which causes it to become deenergized sufficiently to release its front contacts. Circuits through the relay contacts control the operation of wayside signals in the usual manner. Line circuit current flows from the line circuit transformer to the middle point of a comparatively high resistance bridged across the rails at the relay end of the block, through the two halves of the resistance and along the rails of the track in multiple, through a similar resistance at the other end of the block to the middle point of the resistance unit and through a line wire back to the transformer. From the description of the circuits it is evident that track circuit current flows away from the transformer on one rail of the track and back on the other rail, that is, the current flows in opposite directions in the two rails whereas the line circuit current is evenly divided between the rails and flows in the same direction in each rail. The track circuits are adjusted for normal operation under clear or caution conditions so that there will be 0.8 ampere in the rails at the relay end of the circuit as a train enters the block and the line circuit is adjusted to give total line circuit current 0.8 ampere or 0.4 ampere in each rail.

There are two receivers located on the locomotive just ahead of the front wheels called track circuit receivers and a similar pair of receivers farther back on the locomotive or on the tender known as line circuit receivers. The receivers are supported a few inches above the rails of the track and coils in each pair of receivers are connected in series. The connections are such that, on account of the direction of the flow of current in the rails, the track circuit receivers are energized inductively by track circuit current and are not influenced by line circuit current and the line circuit receivers are energized by line circuit current and are not affected by current in the track circuit. There is a two-circuit vacuum tube amplifier with four tubes employed in the locomotive equipment to amplify the small voltages induced in the receiver coils. The input circuits of the amplifier are connected separately to the front and rear receivers and the output circuits are connected to corresponding windings of the primary relay. The amplifying apparatus is carefully adjusted so that when the track circuit and line circuit currents in the rails are in time phase, the currents in the relay windings will also be in phase in which case no torque will be developed on the rotor shaft of the relay. If the phase of the current in either the track circuit or the line circuit is varied the corresponding current in the relay follows the phase of the rail current. The phase displacement between the currents in the relay windings under any condition of operation is therefore the same as the phase displacement between the currents in the rails. The size of the current in the relay windings relative to the corresponding rail currents is shown in Fig. 2.

*Conditions of the Track.* The rails of the track are A. S. C. E. section, 100 lb. per yd., bonded with 2 No. 6 copper-clad bond wires 54 in. long having a loop impedance 0.25 ohm per 1000 ft., power factor 0.5, and the ballast is mostly stone ballast having a resistance varying between 5 ohms and 20 ohms per 1000 ft. of track. The leakage resistance of two rails in multiple to ground is taken as 2 ohms per 1000 ft. in wet weather and 12 ohms per 1000 ft. in dry weather. The length of the track circuit is 6000 ft.

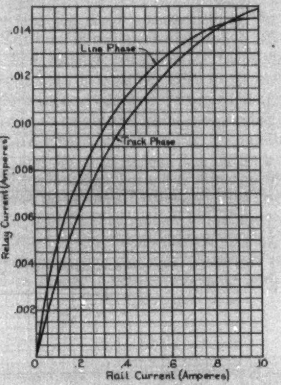

FIG. 2—RELATION BETWEEN CURRENT IN THE RELAY AND CURRENT IN THE RAILS

*Characteristics of the Track Relay.* Local Phase: Impedance 440 ohms, power factor 0.656; current at 110 volts, 0.25 ampere; phase of current relative to voltage ⦢ 49 deg.

NOTE: The inverted angle sign ⦢ indicates a lagging current or voltage whereas the usual angle sign ∠ indicates a leading current or voltage relative to the voltage at the secondary of the transformer. This notation will be employed hereafter in tabulating currents or voltages to describe phase relations.

Track Phase: Impedance 0.64 ohm, power factor 0.656; operating currents with 90 deg. phase displacement. Current to pick up relay to make front stop, 0.22 ampere. Current to pick up relay to close front contacts, 0.19 ampere. Current to allow relay to release its contacts, 0.11 ampere.

*Adjustment of the Track Circuit.* On a steam operated road without train control, the track circuit would be adjusted under wet weather conditions with a limiting impedance of 4 ohms but with this adjustment when a train is entering the block there would not be the required current 0.8 ampere in the rails for the operation of the train control equipment. To increase the current in the rails the amount of limiting impedance might be reduced but it would be better for the purpose of improving the shunting, to retain the 4 ohms limiting impedance and increase the voltage on the track trasformer to give 0.88 ampere, (*i. e.,* 0.8 ampere + 10 per cent to allow for drop in transmission line voltage) and insert a variable resistance in series with the track relay as shown in Fig. 1 to limit the current in the relay sufficiently to give satisfactory normal operation.

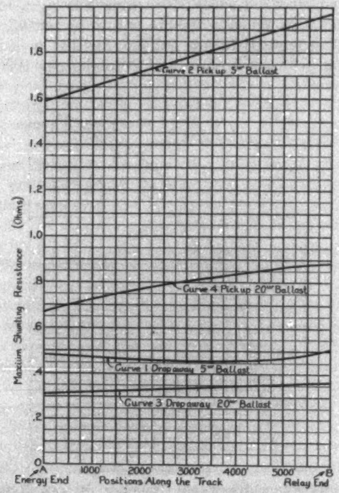

FIG. 3—MAXIMUM SHUNTING RESISTANCES AFFECTING THE TRACK RELAY AS A TRAIN PASSES THROUGH THE BLOCK

Without considering train control, minimum operation of the track relay would be obtained with 3.1 volts at the transformer giving a current 0.26 ∠ 117 deg. 33 min. ampere in the relay but to get sufficient current in the rails for train control operation the voltage will have to be increased to 7 volts which gives 0.875 ∠ 106 deg. 41 min. ampere in the rails as a train enters the block. The variable resistance in series with the relay is then adjusted when the block is unoccupied to 1.75 ohms giving 0.316 ∠ 101 deg. 24 min. ampere in the relay (equivalent current at 90 deg. phase displacement 0.25 ampere). With this adjustment in dry weather when the ballast resistance is 20 ohms per 1000 ft. the current in the relay will increase to 0.706 ∠ 75 deg. 7 min. ampere (equivalent current at 90 deg. phase displacement 0.311 ampere) and the current in the rails at the relay end of the circuit as a train enters the block will be 1.185 ∠ 85 deg. 34 min. amperes.

*Shunting of the Track Relay.* Ordinarily with a properly adjusted track circuit when a train enters a block the track relay becomes shunted but in the case of a poorly adjusted circuit under adverse rail conditions it might happen that the relay would not shunt or if the relay shunts properly as a train enters a high shunting resistance might allow the relay to pick up and the train loses its shunt. To determine the shunting characteristics of the track circuit, calculations have been made which show the maximum shunting resistance which will cause the relay to release its contacts and also the resistance which will just allow the relay to pick up again as the train passes through the block. The curves 1 and 3 in Fig. 3 show the maximum shunting resistances for different positions along the track throughout the entire length of the block which will cause the relay to release its contacts and curves 2 and 4 resistances which will allow the relay to pick up to just close its front contacts.

In Table I numerical values are given of the data shown on the curves and also values of current in the relay when the corresponding maximum shunting resistances are connected across the rails. The formulas employed in calculating these maximum shunting resistances at intermediate positions in the block are given in Appendix I.

*Characteristics of the Primary Relay.* Operating torque on rotor shaft with 90 deg. phase displacement:

To cause sector to operate to front stop 0.45 in. - oz.
To pick up to just make front contacts 0.38 in. - oz.
To release front contacts 0.24 in. - oz.

The relation between torque and currents in the relay is expressed by the following equation:

$$T = I_L I_T K \sin \phi$$

Where T = Torque on rotor shaft
$I_L$ = Current in line phase
$I_T$ = Current in track phase
$\phi$ = Difference in phase between $I_L$ and $I_T$
$K$ = 4500

The value of $K$ is practically constant for all operating conditions.

If the size of the line circuit current in the rails is known at any position on the track the operating current in the rails in the track circuit can be determined at 90 deg. phase displacement to produce any required torque in the primary relay. To accomplish this, knowing the line current in the rails, the corresponding current in the relay is determined from curves in Fig. 2 and knowing the torque (as given above for pick-up and drop-away conditions) the current in the track

TABLE I

MAXIMUM SHUNTING RESISTANCE AS AFFECTING OPERATION OF THE TRACK RELAY

| | 5 ohm ballast | | | |
|---|---|---|---|---|
| | Maximum shunting resistance (ohms) | | Current in relay when shunt is applied (amperes) | |
| Positions along the track | Pick-up | Drop-away | Pick-up | Drop-away |
| At *A* end | 1.585 | 0.485 | 0.21 ∠ 115 deg. 11 min. | 0.113 ∠ 126 deg. 20 min. |
| 1500 ft. from *A* | 1.68 | 0.468 | 0.21 ∠ 110 deg. 20 min. | 0.116 ∠ 120 deg. 6 min. |
| 3000 ft. from *A* | 1.783 | 0.459 | 0.223 ∠ 107 deg. 39 min. | 0.121 ∠ 114 deg. 17 min. |
| 4500 ft. from *A* | 1.87 | 0.464 | 0.224 ∠ 107 deg. 23 min. | 0.122 ∠ 113 deg. 19 min. |
| At *B* end | 1.97 | 0.505 | 0.225 ∠ 106 deg. 28 min. | 0.123 ∠ 112 deg. 46 min. |

| | 20 ohm ballast | | | |
|---|---|---|---|---|
| | Maximum shunting resistance (ohms) | | Current in relay when shunt is applied (amperes) | |
| Positions along the track | Pick-up | Drop-away | Pick-up | Drop-away |
| At *A* end | 0.672 | 0.314 | 0.227 ∠ 105 deg. 51 min. | 0.123 ∠ 112 deg. 3 min. |
| 1500 ft. from *A* | 0.75 | 0.327 | 0.251 ∠ 98 deg. 10 min. | 0.134 ∠ 104 deg. 5 min. |
| 3000 ft. from *A* | 0.81 | 0.34 | 0.263 ∠ 95 deg. 30 min. | 0.141 ∠ 99 deg. 30 min. |
| 4500 ft. from *A* | 0.855 | 0.356 | 0.275 ∠ 92 deg. 44 min. | 0.148 ∠ 97 deg. 4 min. |
| At *B* end | 0.887 | 0.366 | 0.29 ∠ 89 deg. 53 min. | 0.156 ∠ 93 deg. 51 min. |

circuit windings of the relay can be determined from the above formula. The track circuit rail current is then determined from the curve. Numerical values of track circuit currents to give pick-up and drop-away of the relay with a train at different positions on the track will be given after a study has been made of the line circuit.

*Current in the Rails under the Receivers.* Most of the current in the line circuit flows through the rails in multiple but there is a small amount of current that flows through the ground as shown in Fig. 4. The leakage current flows from the rails to ground in one-half of the circuit from *A* to *C* and flows back from the ground into the rails in the other half of the circuit from *C* to *B*. Tests have been made in the field of the amount of current flowing in the rails throughout the length of a block with a vacuum tube testing apparatus used in connection with a search coil on a laminated iron structure that was placed over the rail. The curves obtained show that the current in the rails follows very closely to the shape of the common catenary or cosh curve and for that reason the conductance to ground is assumed to be evenly distributed and line circuit currents have therefore been computed from well known hyperbolic formulas. The condition shown in Fig. 4 may also be represented as shown in Fig. 5 in which the ground is assumed to have zero resistance and is represented as a neutral plane. For uniformity in the use of formulas in making calculations the line circuit may be considered as if it were a two-conductor circuit 3000 ft. in length having evenly distributed leakage giving the same attenuation in Fig. 5 as in Fig. 4. The loop impedance is taken as 0.125 ohm per 1000 ft., and leakage resistance of twice the values given above, *i. e.*, 4 ohms per 1000 ft. in wet weather and 24 ohms in dry weather. The attenuation in the latter case is so small that it may be neglected. The complete line circuit shown in Fig. 1 contains mostly resistance and for that reason the current from the transformer as it enters the rails at either end of the block is assumed to be in phase with the voltage at the transformer and it is further assumed that the voltage at the secondaries of the transformers supplying the track and line circuits and the local circuit of the track relay are in phase. Calculations have been made of the line circuit current in the rails at different positions along the track and the results are given in Table II. The table also shows corresponding values of current in the relay taken from the curves in Fig. 2.

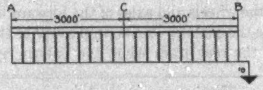

FIG. 4—EVENLY DISTRIBUTED LEAKAGE BETWEEN TWO RAILS IN MULTIPLE AND GROUND

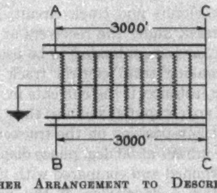

FIG. 5—ANOTHER ARRANGEMENT TO DESCRIBE CONDITION SHOWN IN FIG. 4

Having determined the line circuit currents in the relay and knowing the torque characteristics the corresponding currents in the track circuit windings can be determined by use of the formula given above assuming 90 deg. phase displacement. For a train at different positions on the track numerical values of the current have been computed to cause the relay to operate to its front stop, to pick up to just close its front contacts, and to release the contacts. These

TABLE II

LINE CIRCUIT CURRENT IN THE RAILS AND CORRESPONDING CURRENT IN THE RELAY

Ballast 5 Ohms per 1000 ft.

| Positions along the track | Currents in rails | Current in relay |
|---|---|---|
| At *A* end........ | 0.88 ∠ 0 deg. ampere | 0.0144 ampere |
| 1000 ft. from *A*.. | 0.87 ∠ 1 deg. ampere | 0.01435 ampere |
| 2000 ft. from *A*.. | 0.86 ∠ 3 deg. ampere | 0.0143 ampere |
| 3000 ft. from *A*.. | 0.817 ∠ 6 deg. 30 min. ampere | 0.0142 ampere |
| 4000 ft. from *A*.. | 0.86 ∠ 3 deg. ampere | 0.0143 ampere |
| 5000 ft. from *A*.. | 0.87 ∠ 1 deg. ampere | 0.01435 ampere |
| At *B* end........ | 0.88 ∠ 0 deg. ampere | 0.0144 ampere |

Ballast 20 ohms per 1000 ft.

In this case the current in the rails at any position on the track is 0.88 ∠ 0 deg. ampere and the current in the relay is 0.0144 ampere.

TABLE III

PICK UP AND DROP AWAY CHARACTERISTICS OF PRIMARY RELAY IN TERMS OF TRACK CIRCUIT CURRENT IN THE RELAY AND CORRESPONDING CURRENT IN THE RAILS AT 90 DEG. PHASE DISPLACEMENT

| | Pick-up to just make front stop | | Pick-up to just make front contacts | | Drop-away to release contacts | |
|---|---|---|---|---|---|---|
| Positions along the track | Current in relay (amperes) | Current in rails (amperes) | Current in relay (amperes) | Current in rails (amperes) | Current in relay (amperes) | Current in rails (amperes) |
| At *A* end.............. | 0.00695 | 0.233 | 0.00587 | 0.186 | 0.0037 | 0.11 |
| 1000 ft. from *A*........ | 0.00697 | 0.234 | 0.00589 | 0.187 | 0.00372 | 0.111 |
| 2000 ft. from *A*........ | 0.007 | 0.235 | 0.00592 | 0.188 | 0.00373 | 0.112 |
| 3000 ft. from *A*........ | 0.00705 | 0.236 | 0.00596 | 0.189 | 0.00376 | 0.113 |
| 4000 ft. from *A*........ | 0.007 | 0.235 | 0.00592 | 0.188 | 0.00373 | 0.112 |
| 5000 ft. from *A*........ | 0.00697 | 0.234 | 0.00589 | 0.187 | 0.00372 | 0.111 |
| At *B* end.............. | 0.00695 | 0.233 | 0.00587 | 0.186 | 0.0037 | 0.11 |

values are given in Table III together with corresponding track circuit currents in the rails which have been taken from the curves in Fig. 2. In making track circuit calculations to determine the performance of a track relay the pick-up and drop-away characteristics are usually given in terms of the current in the track and local windings of the relay at 90 deg. phase displacement. The data in Tables II and III give the operating characteristics of the primary relay in terms of line circuit and track circuit current in the rails of the track under the receivers at 90 deg. phase displacement, and are intended to be used in a similar manner in making train control track circuit calculations. For instance, if the currents in the rails under the receivers are computed and also their phase relation for a train at any position on the track, the equivalent track circuit current at 90 deg. phase displacement may then be determined and compared with the data in the tables to obtain a knowledge of the performance of the relay.

In this discussion the data in the tables have been employed in connection with formulas given in Appendix II in making calculation of the shunting characteristics of the circuit.

*Shunting of the Track as Affecting the Primary Relay.* In a train control track circuit energy is always fed to the rails at the end of the block ahead of the train when the block is occupied. If a shunt is connected across the rails at any position in the block in advance of the train the track circuit current would flow through the shunt path and there would be practically no track circuit current under the receivers on the train with the result that the primary relay would become deenergized and release its contacts. The operation of the relay would immediately start the train controlling mechanism in operation to control the speed of the train automatically. In practise a shunt across the rails may be through a circuit controller at an open switch or it may be due to a train ahead in the same block.

Two conditions of shunting have been considered; first, with a forward train the middle of the block and the following train entering and approaching the train ahead; second, with a forward train at the exit end of the block and the rear train entering and proceeding into the block. The most difficult condition of shunting has been considered in which it is assumed that the resistance through the wheels and axles on the rear train is negligible. In each case calculations have been made to determine the maximum shunting resistance through the wheels and axles of the forward train which will cause the pick-up or the drop-away of the primary relay on the rear train when the ballast resistance is 5 ohms and also when it is 20 ohms per 1000 ft. of track. The results of the calculations are plotted in curves in Figs. 6 and 7. Curves in Fig. 6 are for the case where the forward train is in the middle of the block and Fig. 7 where the forward train is at the leaving end of the block. In both figures, curves 1 and 2 show the maximum resistances of the shunt of the forward train which

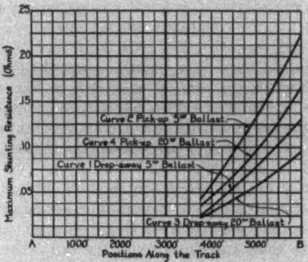

Fig. 6—Curves Showing Maximum Shunting Resistances When Forward Train is in the Middle of a Block and a Following Train is Entering and Approaching From the Relay End

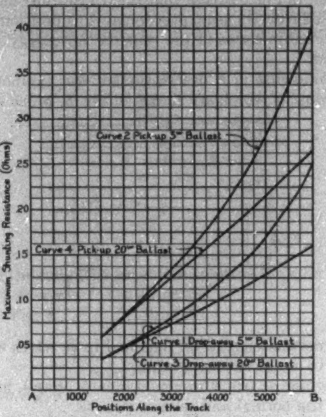

Fig. 7—Curves Showing Maximum Shunting Resistance When Forward Train is at the Energy End of a Block and a Following Train Entering and Approaching From the Relay End

will prevent the relay on the rear train from picking up and the resistances which will cause the relay to drop away respectively when the ballast is 5 ohms per 1000 ft. and curves 3 and 4 give the maximum resistances when the ballast is 20 ohms per 1000 ft. Numerical data from which these curves are plotted and also corresponding values of track circuit current in the rails under the receivers on the rear train are given in Tables IV and V.

The method of making these shunting calculations in train control track circuits is described in Appendix II.

## Conclusions

In Fig. 3 the curves 3 and 4 describe the shunting of the track relay as a train passes through the block during dry weather conditions. The resistance of the shunt must be less than 0.366 ohm as shown on curve 3 when the train enters the block to cause the relay to release its contacts and as the train proceeds the resistance must remain less than the resistances shown on curve 4 to prevent the relay from picking up. If the relay should pick up, the shunting resistance must decrease again below the values shown on curve 3 to cause the relay to release its contacts.

The curves in Figs. 6 and 7 describe the shunting

TABLE IV

TRAIN CONTROL, MAXIMUM SHUNTING RESISTANCES FORWARD TRAIN IN MIDDLE OF THE BLOCK

| | 5 ohm ballast | | | |
|---|---|---|---|---|
| | Maximum shunting resistance (ohms) | | Current in rails under receivers (amperes) | |
| Position of rear train | Pick-up | Drop-away | Pick-up | Drop-away |
| At *B* end............. | 0.227 | 0.132 | 0.285 ∠ 139 deg. 14 min. | 0.186 ∠ 143 deg. 50 min. |
| 5000 ft. from *A*........ | 0.132 | 0.078 | 0.284 ∠ 138 deg. 49 min. | 0.181 ∠ 143 deg. 5 min. |
| 4000 ft. from *A*........ | 0.058 | 0.0346 | 0.255 ∠ 135 deg. 27 min. | 0.143 ∠ 141 deg. 12 min. |

| | 20 ohm ballast | | | |
|---|---|---|---|---|
| | Maximum shunting resistance (ohms) | | Current in rails under receivers (amperes) | |
| Position of rear train | Pick-up | Drop-away | Pick-up | Drop-away |
| At *B* end............. | 0.168 | 0.096 | 0.263 ∠ 134 deg. 58 min. | 0.163 ∠ 137 deg. 38 min. |
| 5000 ft. from *A*........ | 0.097 | 0.058 | 0.256 ∠ 133 deg. 16 min. | 0.16 ∠ 136 deg. 33 min. |
| 4000 ft. from *A*........ | 0.045 | 0.029 | 0.252 ∠ 132 deg. 27 min. | 0.152 ∠ 136 deg. 20 min. |

TABLE V

TRAIN CONTROL, MAXIMUM SHUNTING RESISTANCES FORWARD TRAIN AT ENERGY END OF BLOCK

| | 5 ohm ballast | | | |
|---|---|---|---|---|
| | Maximum shunting resistance (ohms) | | Current in rails under receivers (amperes) | |
| Position of rear train | Pick-up | Drop-away | Pick-up | Drop-away |
| At *B* end............. | 0.405 | 0.25 | 0.312 ∠ 143 deg. 27 min. | 0.208 ∠ 148 deg. 1 min. |
| 4000 ft. from *A*........ | 0.196 | 0.118 | 0.286 ∠ 138 deg. 53 min. | 0.172 ∠ 142 deg. 26 min. |
| 2000 ft. from *A*........ | 0.082 | 0.049 | 0.257 ∠ 136 deg. 3 min. | 0.17 ∠ 138 deg. 52 min. |

| | 20 ohm ballast | | | |
|---|---|---|---|---|
| | Maximum shunting resistance (ohms) | | Current in rails under receivers (amperes) | |
| Position of rear train | Pick-up | Drop-away | Pick-up | Drop-away |
| At *B* end............. | 0.266 | 0.161 | 0.262 ∠ 134 deg. 43 min. | 0.167 ∠ 138 deg. 42 min. |
| 4000 ft. from *A*........ | 0.168 | 0.101 | 0.26 ∠ 134 deg. 19 min. | 0.164 ∠ 137 deg. 54 min. |
| 2000 ft. from *A*........ | 0.083 | 0.050 | 0.261 ∠ 138 deg. 28 min. | 0.163 ∠ 137 deg. 38 min. |

requirements for safe operation of the train control equipment. For instance, during dry weather conditions when there is a train in the middle of a block and a following train is entering the block, curve 3 in Fig. 6 shows that the resistance of the shunt of the forward train must be less than 0.096 ohm to cause the primary relay on the rear train to release its contacts and the resistance must remain less than the values shown on curve 4 to prevent the relay from picking up as the train proceeds into the block. If the relay should pick-up the shunting resistance must be reduced to a value less than those shown on curve 3 to cause the relay to drop away again.

In the ordinary track circuit, the wheels of a train shunt out the track relay in series with the rails of the track but in the case of a forward train shunting current from a rear train there is only the impedance of the rails between the two trains and the impedance through the wheels and axles of the rear train to be shunted. The effect of the shunting on the primary relay is not as good as the shunting of the track relay and the shunting effect on the primary relay on a following train becomes poorer as the train runs closer to the train ahead.

In short train control track circuits, the condition of the ballast has little effect on the shunting of the primary relay but in longer circuits, a mile or more in length, the ballast resistance has a considerable effect. The curves show that the shunting is better during wet weather than it is under dry weather conditions.

## Appendix I

### INTERMEDIATE SHUNTING IN A-C. STEAM ROAD TRACK CIRCUITS

It is possible to determine the maximum shunting resistance in either a-c. steam or electric road track circuits by using the general formula for shunting.

$$G = \frac{E\,Y}{I_S} - K$$

This formula in either case may be employed when a shunt is connected at either end of a track circuit or at any intermediate position along the track. In solving any problem for shunting it is first necessary to determine the values of $Y$ and $K$ and for this purpose formulas have been given in a previous article[2] for determining these values in a steam road track circuit in cases where the shunt is applied at either end of the circuit. It is intended in this appendix to derive the formulas for $Y$ and $K$ that have been used in making calculations of shunting of the track relay at intermediate positions along the track.

The diagram in Fig. 8 is the ordinary steam road track circuit in which $A\,B$ is a track section to which there is a shunt connected across the rails at an intermediate position $C$. The circuit shown in Fig. 9 is the same as the circuit in Fig. 8 except that the transformer has been transposed from its usual position at $A$ to position $C$ and is connected in series in the rails on the energy side of the shunt.

The following is a description of the symbols employed most of which are shown in Fig. 8, which we will call the normal circuit, or that in Fig. 9, which will be referred to as the reverse circuit.

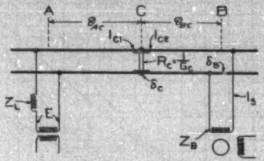

FIG. 8

$E$ = voltage at transformer (standard phase), in both the normal and reverse circuits.

$i$ = equivalent current in the relay at 90 deg. phase displacement, which will just cause the relay to drop away or in determining loss of train shunt it is the value of current which just allows the relay to pick up sufficiently to make its contacts.

$G_C$ = minimum shunting conductance when a shunt is applied at $C$.

$R_C$ = maximum shunting resistance when shunt is applied at $C$.

The above quantities are considered as real quantities whereas those that follow are complex quantities.

$Z_B$ = impedance of relay and leads to track.

$Z_L$ = limiting impedance including leads to track.

$z_0$ = surge impedance of the track.

$\theta$ = hyperbolic angle subtending portions of the track as indicated by subscripts.

$\delta_B = \tanh^{-1} \dfrac{Z_B}{z_0}$ = position angle at $B$ in normal circuit

$\delta_C = \delta_B + \theta_{BC}$ = position angle at $C$ in normal circuit

$I_S$ = current in relay when shunt is applied.

$I_{C_2}$ = current in rails on relay side of shunt in normal circuit.

$I_{C_1}$ = current in rails on energy side of shunt in normal circuit.

$\delta_A' = \tanh^{-1} \dfrac{Z_L}{z_0}$ = position angle at $A$ in reverse circuit.

$\delta_C' = \delta_A' + \theta_{AC}$ = position angle at $C$ in reverse circuit.

$I_A'$ = current in limiting impedance in reverse circuit.

$I_{C_1}'$ = current flowing through transformer in reverse circuit (impedance of transformer secondary is assumed negligible).

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[2] *Shunting in A-C. Track Circuits*, By C. F. Estwick, A. I. E. E. JOURNAL, December 1921, p. 919.

From the theory of the reverse circuit it will be understood that the current $I_{C1}$ in Fig. 8 is the same as current $I_A'$ in the reverse circuit in Fig. 9. With this principle in mind the following algebraic solution may be understood by reference to the diagrams.

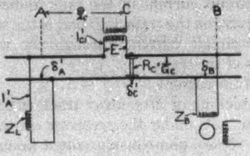

Fig. 9

From Fig. 8

$$I_{C2} = I_S \times \frac{\cosh \delta_C}{\cosh \delta_B} \tag{1}$$

and from Fig. 9

$$I_{C1}' = \frac{E}{\dfrac{R_C\, z_0 \tanh \delta_C}{R_C + z_0 \tanh \delta_C} + z_0 \tanh \delta_C'} \tag{2}$$

and $$I_{C1} = I_A' = I_{C1}' \times \frac{\cosh \delta_A'}{\cosh \delta_C'} \tag{3}$$

From Fig. 8

$$I_{C2} = I_{C1} \times \frac{R_C}{R_C + z_0 \tanh \delta_C} \tag{4}$$

Combining the above equations

$$I_S \times \frac{\cosh \delta_C}{\cosh \delta_B} = \frac{E}{\dfrac{R_C\, z_0 \tanh \delta_C}{R_C + z_0 \tanh \delta_C} + z_0 \tanh \delta_C'} \times \frac{\cosh \delta_A'}{\cosh \delta_C'} \times \frac{R_C}{R_C + z_0 \tanh \delta_C} \tag{5}$$

Simplifying the second member

$$I_S \times \frac{\cosh \delta_C}{\cosh \delta_B} = \frac{E\, R_C}{R_C (z_0 \tanh \delta_C + z_0 \tanh \delta_C') + z_0^2 \tanh \delta_C \tanh \delta_C'} \times \frac{\cosh \delta_A'}{\cosh \delta_C'} \tag{6}$$

For simplicity substitute

$$a = \frac{\cosh \delta_C}{\cosh \delta_B} \quad b = z_0 \tanh \delta_C \quad c = z_0 \tanh \delta_C'$$

$$d = \frac{\cosh \delta_A'}{\cosh \delta_C'} \tag{6a}$$

Then $$I_S\, a = \frac{E\, R_C\, d}{R_C (b + c) + b\, c} \tag{7}$$

Remembering that $G_C = 1/R_C$

$$I_S\, a = \frac{E\, d}{G_C\, b\, c + (b + c)} \tag{8}$$

Whence $$G_C = \frac{E\, d}{I_S\, abc} - \frac{b + c}{bc} \tag{9}$$

Expanding we have

$$G_C = \frac{E \cosh \delta_A' \cosh \delta_B}{I_S \cosh \delta_C \cosh \delta_C'\, z_0^2 \tanh \delta_C \tanh \delta_C'} - \frac{z_0 (\tanh \delta_C + \tanh \delta_C')}{z_0^2 \tanh \delta_C \tanh \delta_C'} \tag{10}$$

or $$G_C = \frac{E \cosh \delta_A' \cosh \delta_B}{I_S\, z_0^2 \sinh \delta_C \sinh \delta_C'} - \frac{\tanh \delta_C + \tanh \delta_C'}{z_0 \tanh \delta_C \tanh \delta_C'} \tag{11}$$

This formula is used for determining the minimum conductance or maximum resistance of a shunt at an intermediate position on the track.

When the shunt is transferred to the $A$ end of the track, this formula reduces to

$$G_A = \frac{E \cosh \delta_B}{I_S\, Z_L\, z_0 \sinh \delta_A} - \frac{Z_L + z_0 \tanh \delta_A}{Z_L\, z_0 \tanh \delta_A} \tag{12}$$

And when the shunt is at the $B$ end the formula becomes

$$G_B = \frac{E \cosh \delta_A'}{I_S\, Z_B\, z_0 \sinh \delta_B'} - \frac{Z_B + z_0 \tanh \delta_B'}{Z_B\, z_0 \tanh \delta_B'} \tag{13}$$

From the above formula for intermediate shunting we then have

$$Y = \frac{\cosh \delta_A' \cosh \delta_B}{z_0^2 \sinh \delta_C \sinh \delta_C'} \tag{14}$$

$$K = \frac{\tanh \delta_C \tanh \delta_C'}{z_0 \tanh \delta_C \tanh \delta_C'} \tag{15}$$

Having determined $Y$ and $K$ the maximum shunting resistances and corresponding currents in the relay can be computed in the manner already described in the previous article referred to above, however, to make this discussion more complete the formulas employed are given below.

Let $\gamma$ = Slope of track phase current in relay (degrees)
$\beta$ = Slope of local phase current in relay (degrees)
$\phi = \beta - \gamma$ = Phase displacement (degrees)
$y$ = Size of $Y$
$v$ = Slope of $Y$ (degrees)

$m$, $n$, $e$, and $f$ are numerical values obtained from the following equations

$$\frac{E\, y}{i} \angle (v - \beta) = m + j\, n \text{ and } - K = e + j\, f \tag{16}$$

Then, when $\phi$ is positive (as it is in all cases considered above),

$$G_C = e - \frac{n}{2} \pm \sqrt{\left(\frac{n}{2}\right)^2 - mf - f^2} \qquad (17)$$

In this formula the proper sign before the radical is used to determine $G_C$ as a positive quantity.

Then $R_C = 1/G_C$

$$\gamma = v - \tan^{-1}\left(\frac{-f}{G_C - e}\right) \qquad (18)$$

and

$$I_B = \frac{i}{\sin \phi} \angle \gamma \qquad (19)$$

In the last formula $\sin \phi$ is always taken as positive.

Numerical examples given in the previous paper will show more clearly how these formulas are employed.

## Appendix II

### SHUNTING IN TRAIN CONTROL TRACK CIRCUITS

In the train control track circuit shown schematically in the diagram Fig. 10 there are two trains in the block at positions $C$ and $D$. It is required to determine the resistance of the shunt through the wheels and axles of the train at $C$ which will just cause the primary relay on the train at $D$ to release its front contacts or the resistance of the shunt which will just allow the relay to pick up and close the contacts. The resistance of the shunt of the following train at $D$ is assumed to be negligible and short-circuits the track relay and the rails in the rear of the train. The formulas for shunting are derived in a manner very similar to those in Appendix I for shunting of the track relay at an intermediate position in the block. If the line circuit in Fig. 10 is neglected it can be seen that the circuit in Fig. 11 is the same as the circuit in Fig. 10 except that the transformer has been transposed from its normal position at $A$ in Fig. 10 to position $C$ as shown in Fig. 11. The symbols employed herein are the same as those in Appendix I except as follows:

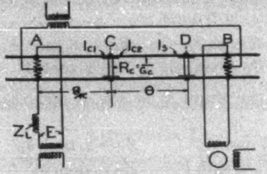

FIG. 10

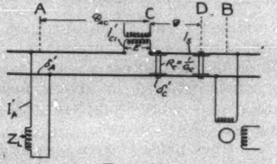

FIG. 11

$I_B$ = track circuit current in the rails under the front receivers on the train at $D$ and is the same as the short-circuit current through the wheels and axles of the train.

$\gamma$ = slope of the current $I_B$.

$i$ = size of pick-up or drop-away track circuit current in the rails under the receivers on the train at $D$ at 90 deg. phase displacement taken from the second and third columns in Table III.

$\beta$ = slope of line circuit current in the rails under the rear receivers on the train at $D$ given in the second column in Table II.

$\theta$ = hyperbolic angle subtending the length of track from $C$ to $D$.

$\delta_B$ and $\delta_C$ are not employed in this case.

Referring to the diagram in Fig. 10 we have

$$I_{C2} = I_B \cosh \theta \qquad (1)$$

and from Fig. 11

$$I_{C1}' = \frac{E}{\dfrac{R_C\, z_0 \tanh \theta}{R_C + z_0 \tanh \theta} + z_0 \tanh \delta_C'} \qquad (2)$$

It will be understood that $I_{C1}$ in Fig. 10 is equal to $I_A'$ in Fig. 11, therefore,

$$I_{C1} = I_A' = I_{C1}' \times \frac{\cosh \delta_A'}{\cosh \delta_C'} \qquad (3)$$

From Fig. 10

$$I_{C2} = I_{C1} \times \frac{R_C}{R_C + z_0 \tanh \delta_C} \qquad (4)$$

Combining the above equations,

$$I_B \cosh \theta = \frac{E}{\dfrac{R_C\, z_0 \tanh \theta}{R_C + z_0 \tanh \theta} + z_0 \tanh \delta_C'} \times \frac{\cosh \delta_A'}{\cosh \delta_C'} \times \frac{R_C}{R_C + z_0 \tanh \theta} \qquad (5)$$

This equation is similar to equation (5) in Appendix I and treated in the same manner gives the following equations for the minimum conductance of the shunt of the train at $C$

$$G_C = \frac{E \cosh \delta_A'}{I_B\, z_0^2 \sinh \theta \sinh \delta_C'} - \frac{\tanh \theta + \tanh \delta_C'}{z_0 \tanh \theta \tanh \delta_C'} \qquad (6)$$

Whence

$$Y = \frac{\cosh \delta_A'}{z_0^2 \sinh \theta \sinh \delta_C'} \qquad (7)$$

and

$$K = \frac{\tanh \theta + \tanh \delta_C'}{z_0 \tanh \theta \tanh \delta_C'} \qquad (8)$$

When the forward train is at $A$ these formulas reduce to

$$G_A = \frac{E}{I_S Z_L z_0 \sinh\theta} - \frac{Z_L + z_0 \tanh\theta}{Z_L z_0 \tanh\theta} \qquad (9)$$

$$Y = \frac{1}{Z_L z_0 \sinh\theta} \qquad (10)$$

$$K = \frac{Z_L + z_0 \tanh\theta}{Z_L z_0 \tanh\theta} \qquad (11)$$

After determining the values of $Y$ and $K$, the solution is completed in the same manner as in Appendix I employing the formulas (**16**) to (**19**).

*Numerical Example.* As an example, consider a case of shunting in which there are two trains in a block, the forward train being in the middle of the section and the following train a distance of 2000 ft. in the rear of the train ahead or at a point 1000 ft. from the entrance end of the block. It is required to determine the maximum shunting resistance through the wheels and axles of the forward train which will cause the primary relay on the rear train to release its front contacts. The loop impedance of the rails is 0.25 ohm per 1000 ft., the ballast resistance from rail to rail is 5 ohms per 1000 ft. and the resistance of the ballast from two rails in multiple to ground is 2 ohms per 1000 ft. of track. The voltage at the line circuit transformer is adjusted so that the total line circuit current from the transformer is 0.88 ampere and the voltage at the track transformer is adjusted to 7 volts. The limiting impedance $Z_L = 4 \angle 83$ deg. ohms.

Line circuit current in the rails under the rear train is $0.87 \nwarrow 1$ deg. ampere as given in Table II. The drop away current in the rails at 90 deg. phase displacement is taken from Table III, $i = 0.111$ ampere.

Let $z = 0.25 \angle 60$ deg. loop impedance of rails per 1000 ft.

$g = 0.2$ conductance of ballast per 1000 ft.

$z_0 =$ surge-impedance of the track

and $\alpha =$ attenuation constant

Then

$$z_0 = \sqrt{z/g} = \sqrt{\frac{0.25 \angle 60^\circ}{0.2}} = 1.12 \angle 30^\circ \text{ ohms}$$

$$\alpha = \sqrt{zg} = \sqrt{0.25 \angle 60^\circ \times 0.2} = 0.224 \angle 30^\circ \text{ hyp.}$$

$$= 0.1935 + j\,0.112 = 0.1935 + j\,\underline{0.0713}$$

$$\theta = 2\,\alpha = 0.387 + j\,\underline{0.143}$$

and
$$\delta_A' = \tanh^{-1}\frac{Z_L}{z_0} = \tanh^{-1}\frac{4 \angle 83^\circ}{1.12 \angle 30^\circ}$$

$$= \tanh^{-1} 3.57 \angle 53^\circ$$

Referring to the Chart Atlas of Complex Hyperbolic Functions[3] Table $XII_A$, we find by inspection from the curves

$$\delta_A' = 0.16 + j\,\underline{0.857}$$

We also have $\theta_{AC} = 3\,\alpha = 0.58 + j\,\underline{0.214}$

and $\delta_C' = \delta_A' + \theta_{AC} = 0.74 + j\,\underline{1.071}$

Referring again to the Chart Atlas we may take out the following functions.

$\sinh\theta = 0.45 \angle 31^\circ\ 30'$ .......... from Table $X\text{–}XI_A$
$\tanh\theta = 0.43 \angle 27^\circ$ .............. from Table $XII_A$
$\cosh\delta_A' = 0.273 \angle 35^\circ$ ........... from Table $X\text{–}XI_A$
$\sinh\delta_C' = 1.283 \angle 94^\circ\ 20'$ ........ from Table $X\text{–}XI_A$
$\tanh\delta_C' = 1.54 \nwarrow 6^\circ\ 40'$ ......... from Table $XII_A$

Employing formulas in Appendix II for train $C$ at an intermediate position in the block.

$$Y = \frac{\cosh\delta_A'}{z_0^2 \sinh\delta_C' \sinh\theta}$$

$$= \frac{0.273 \angle 35^\circ}{1.254 \angle 60^\circ \times 1.283 \angle 94^\circ\ 20' \times 0.45 \angle 31^\circ\ 30'}$$

$$= 0.376 \nwarrow 150^\circ\ 50'$$

and
$$K = \frac{\tanh\delta_C' + \tanh\theta}{z_0 \tanh\delta_C' \tanh\theta}$$

$$= \frac{1.54 \nwarrow 6^\circ\ 40' + 0.43 \angle 27^\circ}{1.12\,L\,30^\circ \times 1.54 \nwarrow 6^\circ\ 40' \times 0.43 \angle 27^\circ}$$

$$= 2.58 \nwarrow 49^\circ\ 50' = 1.665 - j\,1.97$$

or
$$-K = -1.665 + j\,1.97$$

Whence

$y = 0.376 \qquad v = \nwarrow 150^\circ\ 50' \qquad v - \beta = \nwarrow 149^\circ\ 50'$

$$\frac{Ey}{i} \angle (v - \beta) = \frac{7 \times 0.376}{0.111} \nwarrow 149^\circ\ 50'$$

$$= 23.7 \nwarrow 149^\circ\ 50' = -20.5 - j\,11.95$$

we then have

$m = -20.5 \qquad n = -11.95 \qquad e = -1.665 \qquad f = 1.97$

$$G_C = e - \frac{n}{2} \pm \sqrt{\left(\frac{n}{2}\right)^2 - mf - f^2}$$

$$= -1.665 + 5.975 + \sqrt{5.975^2 + 40.4 - 3.88} = 12.83 \text{ mhos}$$

$R_C = 0.078$ ohms

$$\tan^{-1}\left(\frac{-f}{G_C - e}\right) = \tan^{-1}\left(\frac{-1.97}{14.49}\right) = \nwarrow 7^\circ\ 45'$$

$$\gamma = v - \tan^{-1}\left(\frac{-f}{G_C - e}\right) = \nwarrow 150^\circ\ 50' - \nwarrow 7^\circ\ 45'$$

$$= \nwarrow 143^\circ\ 5'$$

$$\phi = \beta - \gamma = \nwarrow 1^\circ - \nwarrow 143^\circ\ 5' = +142^\circ\ 5'$$

$$I_S = \frac{i}{\sin\phi} \angle \gamma = \frac{0.111}{0.615} \nwarrow 143^\circ\ 5' = 0.181 \nwarrow 143^\circ\ 5'$$

It may be seen that the above values of $R_C$ and $I_S$ are given in the second and fourth columns in Table IV.

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[3] Chart Atlas of Complex Circular and Hyperbolic Functions, by A. E. Kennelly, Third Edition, 1924, *Harvard University Press.*

# Electric Conduction in Hard Rubber, Pyrex,
## Fused and Crystalline Quartz

BY HUBERT H. RACE*
Associate, A. I. E. E.

***Synopsis.**—The study of physical and electrical characteristics of insulating materials is of growing importance to the electrical industry because of the ever increasing potentials employed in electric generating and distributing equipment. The particular problem presented in this paper is related to engineering practise because polarization and conduction both result in the conversion of electric energy into heat. This produces increased local and general heating, which may be contributing causes to the progressive deterioration and final breakdown of the insulation. The constant potential method explained in this paper provides a means for studying the inherent voltage-current-time relations which are masked in experiments using alternating applied potential.*

*Part of the material contained in this paper was presented by the writer to the faculty of the Graduate School of Cornell University for the degree of Doctor of Philosophy. The investigation was later continued with the joint support of the Hecksher Research Council and the General Electric Company.*

*Several methods were tried for obtaining conducting surfaces on the specimens for constant potential tests. An improved method was devised for making tests and experimental results on four materials were obtained. Peculiar reversals were observed in the charge and discharge curves for fused quartz.*

*The summary of experimental results is followed by suggestions for further research along similar lines.*

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### APPARATUS AND PROCEDURE

### A. *New Method of Measurement.*

PREVIOUSLY the most precise measurements of the extremely small currents obtained in d-c. tests on good solid dielectrics have involved the use of a quadrant electrometer as a quantitative measuring instrument.

The erratic shifting of the zero point and changing of the sensitivity of an electrometer led the writer to devise a method of measurement which uses the electrometer as a null indicating device, so that changes in sensitivity do not affect the results. The method used is convenient and accurate for a range from $10^{-12}$ to $10^{-18}$ ampere, when the current is changing by only a very small percentage over a period of ten seconds or longer.

The object of the tests reported in this paper was to determine curves of electric current flow as functions of time through certain solid dielectrics after constant potential had either been applied to, or removed from, opposite faces of a flat plate of the sample.

The charge and current curves to be expected when constant potential is applied to such a sample are shown in Fig. 1. The great proportion of the charge is stored almost instantaneously, but because the dielectric is not perfect, the charge collected continues to increase. The curve of charge will approach a straight line whose slope will be zero if the final conductivity is zero, and will be finite if the final conductivity is not zero. The current curve is the first derivative of the charge curve and will have the general character shown. Its shape during the first instants will depend upon the characteristics of the external circuit.

The initial pulse of the current passes in a very small fraction of a second after applying the potential and was not measured in any of the reported tests. For some materials, the stored charge continues to increase for weeks after the potential is applied, and is kept constant. It is this long-time current that has been measured in these tests. When the potential is removed after a long-time charge, the currents are similar but reversed in direction.

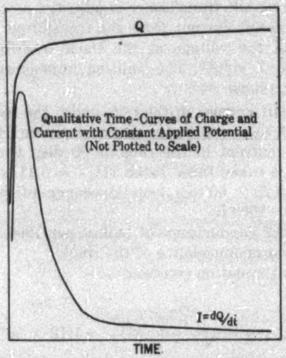

FIG. 1—QUALITATIVE CHARGES AND CURRENT CURVES

The currents obtained are smaller than can be measured with a galvanometer, so that a circuit using a sensitive electrometer was used. The diagram shown in Fig. 2 will help to explain the method of measurement. $C_s$ is the sample to be tested. $C_A$ is an auxiliary air condenser of known capacitance. $P$ is a potentiometer used to vary the potential applied to the lower plate of $C_A$. The quadrant electrometer, *Q. E.*, is used as a very sensitive electrostatic voltmeter to indicate any potential difference between the ground

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For numbers references see Bibliography.

*Presented at Northeastern District No. 1 Meeting of the A. I. E. E., New Haven, Conn., May 9-12, 1928.*

and the isolated system comprising the upper surface of the active area of $C_s$ and the upper plate of $C_A$.

Before applying potential to the lower plate of $C_s$, the upper system is grounded by closing the ground switch shown in Fig. 2. Then when potential is applied, the initial rush of current is conducted through this ground connection. If the ground connection is removed at any time while current is flowing through the specimen, the result will be an accumulation of charge on the isolated plates of $C_s$ and $C_A$, (upper system in Fig. 2). This will result in an increasing potential of the isolated system indicated by a movement of the electrometer spot of light.

Assume first that the electrometer is to be used quantitatively; then the motion of its spot of light should be recorded and interpreted in volts per second, which, when multiplied by the capacitance of the connected system, would give the current flow. However, the difficulties with this method are that the capacitance of the system is difficult to determine accurately, and the capacitance and sensitivity of the electrometer are not constant.

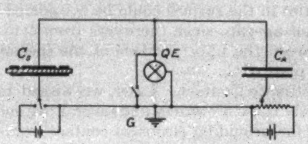

Fig. 2—Simplified Diagram of Connections

Now, as a different method, suppose that after the ground connection has been removed, the slider on $P$ is continually adjusted so as to keep the upper system (though insulated from ground) at ground potential. This is accomplished by so adjusting $P$ that the electrometer spot of light is kept at its zero position. Such an adjustment is possible because any electricity passing from $C_s$ can be drawn onto $C_A$ by properly varying the potential applied to the latter. If at the beginning and end of a certain length of time, the potential of the isolated system is at zero (or any other) potential, all of the current which has passed from $C_s$ in the interval will be collected on $C_A$. The average value of this current will be given by the equation:

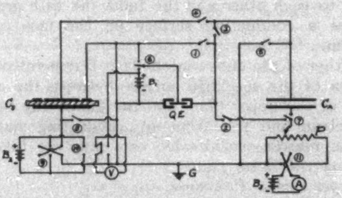

Fig. 3—Complete Diagram of Connections

$$i_{ave} = \frac{\Delta q}{\Delta t} = C_A \frac{\Delta e}{\Delta t} = C_A \left(\frac{e_2 - e_1}{t_2 - t_1}\right) \text{ amperes} \quad (1)$$

where $C_A$ is the capacitance in farads of the auxiliary air condenser and $(e_2 - e_1)$ is the change in potential applied to the lower plate of $C_A$ from $P$ during the interval of time $(t_2 - t_1)$, potential being measured in volts and time in seconds.

For all of the tests, the current was considered positive in the direction in which it was normally flowing while a positive potential was applied to the lower plate of $C_s$. To measure a positive current, it was necessary to apply a negative potential to the lower plate of $C_A$. When the current was reversed, for example during discharge after positive charge, the polarity of $P$ had to be reversed in order to keep the potential of the isolated system zero. During a reading, continuous observation of the electrometer scale was necessary; therefore, the set-up was so arranged that all switching was remotely controlled from the observer's position behind the scale.

The complete diagram of connections is shown in Fig. 3. The positions of all the switches for different conditions of test are given in Table I.

TABLE I
SWITCH POSITIONS FOR DIFFERENT EXPERIMENTAL CONDITIONS

| Switch number | Positions | | | Experimental conditions |
|---|---|---|---|---|
| | *A* | *B* | *C* | |
| 1 | open | closed | open | *A* = Before starting a run and during discharge readings. |
| 2 | open | open | open | |
| 3 | closed | closed | closed | *B* = At very beginning of a run and between charge readings. |
| 4 | closed | closed | closed | |
| 5 | open | open | open | *C* = During readings for charge curve. |
| 6 | down | down | down | |
| 7 | up | up | up | |
| 8 | closed | open | open | |
| 9 | open | right | right | |
| 10 | open | open | open | |
| 11 | down | down | down | |

The elaborate switching system shown in Fig. 3 is not necessary for simple current measurements, but was installed for flexibility in the use of the same equipment for other related tests.

*B. Apparatus.*

$C_s$ is a guard-ring condenser arranged to provide a uniform dielectric field between the parallel surfaces of the specimen and to allow the measurement of the current passing to the middle plate. It is mounted so that potential can be applied to the lower plate.

*Q. E.* is a Compton quadrant electrometer with a platinum sputtered quartz fiber. A potential of about 60 volts has been maintained on the needle for several months. The adjustment is such as to give a sensitivity of from 3000 to 4500 mm./volt, the scale being mounted at two meters. Sensitivities as high as 15,000 mm./volt were obtained but they were accompanied by rather unstable conditions with large shifts of the electrometer zero and were therefore not used. The instrument is shielded from air currents and the case is permanently grounded.

$C_A$ is an air condenser of known capacitance. A 64 by $10^{-12}$ farad fixed condenser having long quartz rods supporting and insulating one set of plates was used for measurement of the smallest currents. A variable parallel-plate air condenser, having a range in capacitance from 76 by $10^{-12}$ to 5360 by $10^{-12}$ farad, was used for measurement of larger currents. For these experiments, this capacitance was used at only three settings, namely, 5360, 1000, and 100. The rotating set of plates was mounted on amber bushings so as to eliminate leakage currents so far as possible.

$P$ is a Queen-Gray potentiometer carrying a normal current of 0.002 ampere with a potential range from zero to 1.91 volts, the smallest graduated division being 0.00001 volt. For large current readings, the potentiometer current was increased ten times, thus multiplying the potential readings by ten.

$A$ is a milliammeter for roughly measuring the current in $P$. Final adjustments were made by checking against a standard cell. The potentiometer current was kept flowing continuously, so as to maintain constant temperature, and therefore constant resistance, in the coils.

$V$ is a voltmeter for measuring either the potential to be applied to the specimen or that on the electrometer needle.

$G$ is the common grounding point for the entire system.

$B_1$ supplies constant potential to the electrometer needle.

$B_2$ is a battery of over 800 volts for supplying any desired potential to $C_s$.

$B_3$ is a 24-volt storage battery supplying the continuous current in $P$.

C. *Preparation of Specimens.*

With Air-Gap. The first series of experiments was made with specimens having polished plane parallel surfaces placed between the plates of a standard air condenser. The upper plate consists of two parts, the center section and a guard-ring. The guard-ring is supported on amber bushings which insulate it from the lower plate. The height of these bushings may be adjusted to give any desired spacing between the plates up to about an inch. The center section is supported from a brass cross-bar which is insulated from the guard-ring by a pair of sulphur bushings. The guard-ring was permanently grounded and the center section, although isolated from ground during a reading, was maintained at ground potential. (See method of making measurements.) Thus, a uniform electric field was maintained in the specimen out to the edge of the guard-ring and fringing was eliminated at the edge of the center section on which measurements were made.

A copper wire, supporting one of the glass mercury cups, was mounted on the isolated center section of the upper plate. A mechanical lever arrangement was provided so that the entire condenser could be rocked, thus moving the mercury cup up and down. An amalgamated copper wire suspended directly from the electrometer quadrants was adjusted to dip in this mercury cup when the latter was in its up position, but to be several millimeters above the surface of the mercury when the cup was down. Thus the connection between $C_s$ and $Q.\ E.$ could easily be made or broken, being remotely controlled from the observer's position behind the electrometer scale.

In the piece of apparatus just described, no attempt was made to provide good electrical contact between the lower surface of the specimen and the brass plate upon which it rested. A small air-gap here due to irregularities in the surface could be considered as part of the total air-gap, since there was from 1 to 2 mm. space between the upper surface of the specimen and the upper plate of $C_s$.

With Intimate Contact. Later, we wished to eliminate entirely these air spaces and several methods were suggested for providing electrical contact between the condenser plates and the surfaces of the specimen. We were prejudiced against the use of mercury contacts by the difficulty of making a suitable guard-ring arrangement, and also by the work of J. E. Shrader[9], who concluded from his experiments that powdered graphite provides better contact than mercury, especially on polished surfaces. We finally decided on two methods of making these contacts: (a) by depositing a metal film on the surface, either by silvering or by sputtering in vacuum, or (b), by painting both the specimen and condenser plate surfaces with India ink in which we had mixed very finely powdered graphite and sticking them together while wet. When dry, they adhere to each other and the India ink with graphite provides a conducting surface on the face of the specimen.

In either of the above methods, it is imperative that the area of the specimen surface between the center section of the upper plate and the guard-ring be perfectly clean and free from any conducting material. For this reason, considerable care must be taken in mounting the brass plates.

D. *Experimental Procedure.*

Detailed Procedure. Before starting a run, to insure that the specimen had no residual polarization, the switches were thrown as shown under $A$, Table I, Under this condition, $C_s$, $Q.\ E.$, and $C_A$ were connected together and isolated from the rest of the set-up, all of which was grounded. If the specimen had any residual polarization, the electrometer would show a drift in one direction or the other; but if the sample were completely depolarized, there would be no electrometer drift, in which case the specimen was ready for test. If the electrometer showed a drift, both plates of the condenser containing the specimen were grounded and left until the residual polarization became zero.

Before starting the experiment, it was also necessary to adjust the potential of $B_2$ to exactly the value required to give the desired potential gradient in the specimen. The voltmeter $V$ was used in making this adjustment.

For aid in describing the exact method of procedure, let us consider the sample data sheet shown in Table II.

At exactly 8:00 p. m., potential was applied to the specimen by throwing switch 9 to the right, switch 1 having been previously closed and switch 8 opened. The charging current was then passing through switch 1 to ground without being measured. The position of all switches is shown in column B, Table I.

TABLE II

SAMPLE DATA SHEET

L. N. hard rubber at a potential gradient of 400 volts/cm.

April 2, 1927 Sample 5 with India ink contacts, $C_A = 1000$

| Time | Minutes | *Q. E.* Zero | *P* Volts | *e* Volts | $i \times 10^{-15}$ Amps. |
|---|---|---|---|---|---|
| 8:00:00 p.m. | 0 | 70.25 | (Applied potential $B_2$ = + 246.5 volts) | | |
| 0:45 | | | 0 | | |
| 1:15 | 1 | | −0.04 | −0.04 | +1333 |
| 1:45 | | | 0 | | |
| 2:15 | 2 | | 0.0245 | 0.0245 | 816.6 |
| 3:30 | | | 0.0025 | | |
| 4:30 | 4 | | 0.027 | 0.0245 | 408.3 |
| 5:30 | | | 0.00145 | | |
| 6:30 | 6 | | 0.01825 | 0.0168 | 280. |
| 7:30 | | | 0 | | |
| 8:30 | 8 | | 0.01305 | 0.01305 | 217.5 |
| 9:30 | | 69.6 | | | |
| 10:00 | | | 0.00115 | | |
| 13:30 | | 69.3 Est.* | | | |
| 14:00 | 12 | | 0.0381 | −0.03695 | 155.2 |
| 14:30 | | 69.15 | | −0.0003 | |
| 15:00 | | | 0.00305 | | |
| 18:30 | | 68.7 Est.* | | | |
| 19:00 | 17 | | 0.0305 | 0.02745 | 114.4 |
| 19:30 | | 68.75 | | | |
| 4/4/27 a.m. | | | | | |
| 11:00:00 | | 64.9 | (Removed Potential) | | |
| 0:45 | | | 0 | | |
| 1:16 | 1 | | +0.04 | +0.04 | −1290 |
| 1:45 | | | 0 | | |
| 2:15 | 2 | | 0.023 | 0.023 | 766.7 |
| 3:30 | | | 0.003 | | |
| 4:30 | 4 | | 0.0259 | 0.0229 | 381.7 |
| 5:30 | | | 0.0025 | | |
| 6:30 | 6 | | (missed the reading) | | |
| 7:30 | | | 0.00295 | | |
| 8:30 | 8 | | 0.01505 | 0.0121 | 201.7 |
| 9:30 | | 64.05 | | | |
| 10:00 | | | 0.0045 | | |
| 13:30 | | 63.6 Est.* | | | |
| 14:00 | 12 | | 0.0367 | +0.0322 | 132.5 |
| 14:30 | | 63.75 | | −0.0004 | |
| 15:00 | | | 0.00363 | | |
| 18:30 | | 63.35 Est.* | | | |
| 19:00 | 17 | | 0.02695 | +0.02332 | 96.33 |
| 19:30 | | 63.45 | | −0.0002 | |

*Estimated.

Exactly 45 sec. later, switch 1 was opened and $P$ was continuously adjusted so as to keep the electrometer spot of light approximately at its zero position. $P$ was carefully adjusted so that the electrometer spot was *exactly* on its estimated zero position at 8:01:15, after which, switch 1 was again closed and the reading of $P$ recorded. The potentiometer slider was then set back to zero ready for the next reading. This process was repeated whenever it was desired to take a reading. At the end of each reading, in fact 30 sec. after closing switch 1, the true position of the electrometer zero was read. If this differed from the estimated position, the reading was corrected for the error, the electrometer calibration having been previously determined. The readings came in rapid succession, at least for the first few hours, after which they could be taken at longer intervals.

Eliminating Switching Errors. The electrometer zero position was not stationary, but was continually shifting. Therefore it seemed necessary, especially for readings of 10 min. duration, to provide a switching arrangement so that the electrometer zero could be accurately determined just before the final adjustment was made at the end of a reading. For this purpose, a mercury cup was provided, into which an amalgamated copper wire could be made to dip. (Switch 3.) When it was desired to determine the electrometer zero without grounding the combination of $C_s$ and $C_A$, switch 3 was opened, switch 1 closed, and the zero position read on the scale. Then switch 1 was opened, switch 3 closed, and the final adjustment of $P$ made to bring the spot of light to its zero position.

There were two possible sources of error in this process.

a. If, when switch 3 was opened, the isolated system was not at ground potential, a certain amount of electricity was removed from the system when the electrometer was grounded. For readings at the very end of a discharge curve, this quantity might be an appreciable proportion of the total charge collected during the 10-min. period.

b. The second source of error was probably the greater, however. It seemed impossible to keep the mercury sufficiently clean to eliminate a contact e. m. f., which was generated every time a switch was opened or closed. It was suggested that a layer of oil might be placed on the mercury to eliminate oxidation and thus prevent this e. m. f. This was not tried, however, because the method already described was devised for taking the data without making any switching operations during a reading.

Minimizing Leakage Errors. The value of current to be measured was so small that extra precautions had to be taken to make sure that electricity did not leak on to the system from some outside source, or that current which we wished to measure, did not leak off without being measured. For these reasons, the entire outfit was surrounded with a permanently grounded electrostatic shield. Also, the set-up was so designed that the isolated system, comprising the upper plate of $C_s$, the electrometer quadrants and one set of plates of $C_A$, was supported entirely by these three pieces of apparatus. Thus, the four chances for leakage from this system were:

1. Surface leakage from the upper plate of $C_s$ to the guard ring;

2. Surface leakage from the free quadrants of *Q. E.* to its case;

3. Surface leakage over the insulating supports, from one set of plates to the other of $C_A$;

4. Conduction through the air due to ionization.

To guard against the first, the surface of the hard rubber was carefully scraped before the guard-ring and upper plate were mounted, the surfaces of the glasses were cleaned with concentrated nitric acid, washed with ammonium hydroxide, and then with distilled water.

The second possibility offers very little chance for leakage since the quadrants were mounted on amber, the surface of which had been highly polished and carefully cleaned.

The third offers a greater chance for leakage. The larger condenser $C_A$ is of the multiple-plate type manufactured for precision radio work. The insulation furnished by the manufacturer was a pressed mica composition. This was found to have relatively large surface leakage and was replaced by Bakelite strips having amber bushings. Even with these precautions, it was found that the combination of the electrometer with $C_A$, $C_s$ being disconnected, showed a leakage drift always in the same direction but varying erratically from 2 by $10^{-15}$ to 10 by $10^{-15}$ amperes. In an attempt to decrease this leakage when reading small currents, a small fixed air condenser was made with one set of plates insulated and supported by long quartz rods. The system leak was thereby reduced to about one-third the previous value.

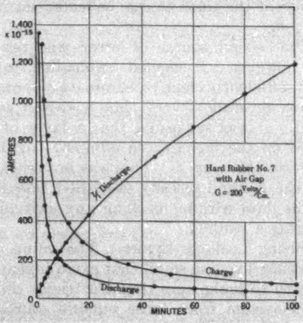

Fig. 4—Hard Rubber No. 7 With Air-Gap

The fact that the observed leakage was always in the same direction leads us to think that some at least was due to the fourth possibility mentioned above, especially in $C_A$ where the air path between plates was relatively short and of large area.

J. J. Thomson[13], in his book "The Conductivity of Electricity Through Gases", quotes C. T. R. Wilson, who, in 1901, showed that in dust-free air, the maximum quantity of electricity which can escape in one second from a charged body in a closed space whose volume is $V$ cu. cm. is about $10^{-8}\ V$ electrostatic units. This equals about 0.333 by $10^{-17}\ V$ coulombs per sec., and is sufficient to account for part, but probably not all, of the leakage observed in our experiments.

Null Method Eliminates Electrometer Errors. The errors that make it inconvenient to use an electrometer as a deflection instrument will be summarized briefly.

It is difficult to determine accurately the capacitance of $C_s$ or the electrometer, and both of these must be known if the deflections are to be interpreted in amperes. The electrometer capacitance changes with any change in the position of the needle. The fast readings are in error because of the inertia of the moving needle and the viscosity of the air surrounding it. More serious than any of these, perhaps, is the fact that the calibration changes with variations of the zero position and other factors; and also that there is not a straight line relation between deflection and the potential on the quadrant.

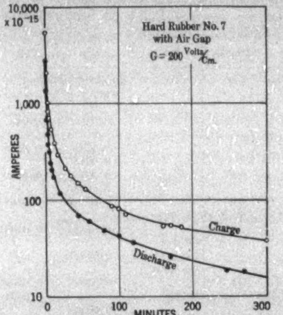

Fig. 5—Hard Rubber No. 7 With Air-Gap

For all of these reasons, while an electrometer is very useful in making relative measurements, it has disadvantages when used as a quantitative instrument. Therefore, the simpler quantitative method already described was devised, using the electrometer only as a very sensitive zero potential indicator.

## Experimental Results

### A. *With Air-Gap.*

As already indicated, the first tests were made with the gap between the upper surface of the specimen and the upper plate of the condenser. A plate of hard rubber and one of Pyrex glass were tested in this way.

In Fig. 4, curve 1 shows the charge curve which although not plotted, was continued for nearly 4000 min., or until the current had decreased to about 15 by $10^{-15}$ amperes. Curve 2 shows the discharge taken after the charge by removing the potential and grounding the lower plate.

Fig. 4 is shown for two reasons: first, to illustrate how rapidly the current drops during the first part of the discharge curve, and yet how long, relatively, it takes for this current to die out entirely. The second reason is embodied in curve 3, in which the reciprocals of the points on curve 2 have been plotted against time. If curve 2 were an hyperbola with the axes for asymptotes, curve 3 would be a straight line passing through the origin. The plot shows very definitely that curve 2 is not a hyperbola.

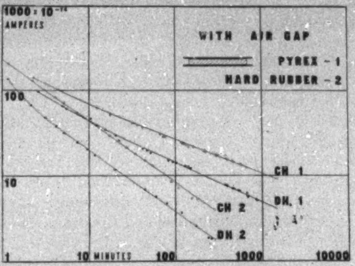

Fig. 6—Hard Rubber No. 7 and Pyrex with Air-Gap

The wide difference between curve 1 and 2 is due to the air-gap, for eliminating the gap eliminated the difference, except for the actual conduction current which is, of course, absent on discharge, (see Figs. 7 and 8). For this reason, subsequent tests were made with intimate contact between the specimen and upper plate of $C_s$.

Fig. 5 shows that the relation between $i$ and $t$ does not even approximately follow a simple exponential law.

The charge and discharge curves for hard rubber, which have been shown in the last two figures plotted in different ways, are plotted in Fig. 6 using logarithmic scales for both current and time ($C\,H - 2$ and $D\,H - 2$). It is seen that the experimental data give practically a straight line relationship between log. $i$ and log. $t$.

$C\,H - 1$ and $D\,H - 1$ are similar charge and discharge curves taken for a sample of Pyrex glass, nearly 15 cm. thick. The principal fact to be gained from these is that the straight relationship makes the polarization an inverse power function of the time:

$$i_p = (\text{const})\ t^{-b} \qquad (2)$$

*B. With Intimate Contact.*

Pyrex Glass. After the curves and $C\,H - 1$ and $D\,H - 1$, shown in Fig. 6, had been obtained, the same specimen was prepared with intimate contact between the surfaces of the specimen and the plates of the condenser. The results of this latter test, plotted in a similar manner, are shown in Fig. 7.

The upper series of circles, through which no line is drawn, are points on the charge curve which is approaching a horizontal asymptote, the final conduction current $I_g$. In the case of Pyrex, $I_g$ is a very appreciable proportion of the charge current.

The series of completely filled dots gives the observed discharge curve, which follows the straight-line law for over 100 min., after which it drops off more rapidly.

The series of half filled circles is obtained by subtracting the value $I_g$ from each of the charge readings, obtaining thereby the effect of polarization alone. These lie superimposed upon the points of the discharge curve showing that the phenomenon is reversible. This relationship may be expressed by the equation:

$$i_p = i\ (\text{charge}) - I_g = -\ i\ (\text{discharge}) \qquad (3)$$

This relation was stated long ago by Curie[1] as a result of the law of superposition.

Although charge curves similar to Fig. 7 are not shown in his published work, the relation represented by eq. (2) was reported by von Schweidler,[10] who obtained discharge curves, similar to those shown in Fig. 7, for mica, paraffin paper, and glass condensers.

A curve for fused quartz obeying the law of eq. (2), was shown by A. Jaquerod and H. Mugeli;[6] but they, like von Schweidler, chose to convert this simple experimentally observed relation to a sum of exponential terms, believing this form easier of theoretical explanation.

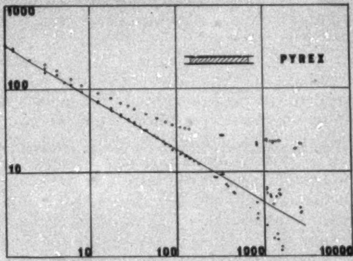

Fig. 7—Pyrex with Intimate Contact

The deviation of observed points in Fig. 7 from the straight-line law may be due to one or both of two causes.

*a.* A slightly erratic unidirectional instrument leak, comparable to the lower values of the curve, was observed. This error decreased the discharge readings but added to the charge readings, the charge current being in the opposite direction to the discharge. The error might well account for the observed departures for the points of $i_{CH} - I_g$ lie above the line and the discharge points lie below it.

*b.* The other possible explanation is that the reaction of the material actually does not obey the law. This can be determined only by further experiment using more refined methods so as to eliminate possible apparatus errors.

Hard Rubber. Fig. 8 shows the results of a series of experiments on two samples of hard rubber. Specimen 7 was tested at four different potential gradients, giving curves 1, 2, 3, and 4. Specimen 5, obtained from a different manufacturer, was tested at only one potential gradient as shown by curve 5. Curves 1, 3, and 4 were taken with a positive potential applied to the lower plate of the condenser. A poor switch contact destroyed the value of the discharge readings for curve 1, so that they were not plotted. Curve 2 was taken with a negative potential applied to the lower plate of the condenser. This shows that the results were independent of the direction of the applied potential.

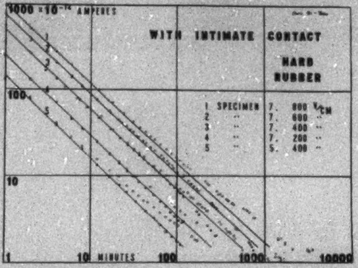

Fig. 8—Hard Rubber No. 5 and No. 7 with Intimate Contact

The unidirectional apparatus errors were found by several tests to be comparable to the value of the final conduction current for hard rubber. In runs 1, 3, and 4, these errors were in the same direction as the final conduction current and therefore add up to give the observed constant value $I_g$. In run 2, the apparatus errors were in the opposite direction to the conduction current, and therefore lowered the charge and raised the discharge curve. Indeed it seems that the errors and the conduction current are about of the same magnitude, for the charge and discharge curves are nearly superimposed. This suggests a way of canceling out the errors, if it is found impossible to remove their cause; namely, to take two runs at each potential gradient under identical conditions, except that the direction of the potential is reversed.

Because the experimental data indicated that the curves were directly proportional to the applied potential, the lines 1, 2, 3, and 4, were so drawn. They are plotted parallel and apart by distances, so that the ordinates of current at any instant are directly proportional to the applied potential gradient. By observing the agreement of the lines with the observed points, the reader may draw his own conclusions regarding this proportionality.

Curve 5 shows that specimen 5, while having approximately the same time rate of change of polarization as specimen 7, gives less than one-third as much polarization under the same conditions. The composition of these two samples is not known to the writer, so no deduction can be made as to the reason for this difference.

The values of $I_g$, taken at the end of each charge curve, included the apparatus errors in the same direction as the actual conduction current. Therefore, the best we can say is that the actual conduction current was equal to, or less than, the observed value; and that the actual apparent resistivity of the material was equal to or greater than that computed using the observed values of $I_g$. (See Table IV.)

Fused Quartz. A sample of fused quartz and one of crystalline quartz on which some previous measurements had been made were obtained from the Bureau of Standards. The writer believes that these are the same samples used by V. E. Whitman[16] in making similar studies on current flow in fused and crystalline quartz. The fused quartz was in the shape of a thin disk with plane parallel faces. It was silver-plated on both sides, with a suitable guard-ring.

Fig. 9 shows a typical example of some of the first measurements made on this sample. No measurements were taken within the first minute after applying or removing the potential and it is impossible to show exactly what was happening at the two extremes of either curve since in this figure they were plotted to uniform scales.

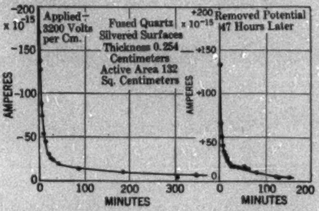

Fig. 9—Fused Quartz with Silvered Surfaces

Several sets of data with different applied potentials were taken with the hope of finding the relation previously shown for hard rubber in Fig. 8. No such relation was found; on the contrary, it was impossible to get the same curve twice with the same applied potential. Also curves obtained with positive applied potential, while of the same form, were not symmetrical with those obtained with a negative applied potential. In fact, the current-time curves for this sample did not seem to obey any quantitative law, but seemed rather to be unaccountably erratic.

It might be well to state here that the upper plate of

$C_s$ (see Figs. 2 and 3) was connected to ground all of the time except while a reading was actually being taken; even then, it was kept at ground potential. Each time before potential was applied the sample was tested to be sure that there was no residual current flowing due to relaxation from some previous charge.

The investigator was gradually convinced that something unexpected, and which he was not observing, was happening during the first minute. Up to this time the first reading for each curve had been taken one min. after applying or removing the potential. Thereafter, the electrometer was used quantitatively, and as many readings as possible obtained during the first minute.

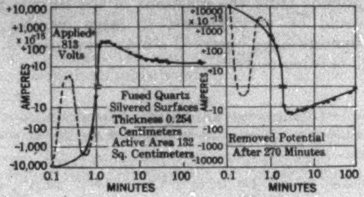

FIG. 10—FUSED QUARTZ WITH SILVERED SURFACES

Fig. 10 represents a typical set of results, the heavy line showing how they were first interpreted. These points give no indication of the current flow between the relatively short observations; and subsequent curves indicated that the data should be interpreted as slow oscillations shown by the dotted curve.

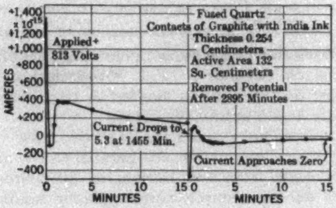

FIG. 11—FUSED QUARTZ WITH GRAPHITE CONTACTS

At first it was suspected that this reversal might be caused by some peculiar condition of resonance in the circuit. This idea was discarded because when an air core inductance of about 400 millihenrys was connected in series with $C_s$, no apparent change was noticed in the charge and discharge curves. Computations also showed that impossible values of circuit constants would be necessary to give a frequency of natural oscillation as low as one cycle per min. Therefore it was concluded that these reversals were either due to the contact surfaces, or else were a characteristic of the material itself.

The next step was to try new contact surfaces. The silver film was removed from the quartz plate, the surfaces were carefully cleaned, and new contacts provided by painting with India ink containing finely powdered graphite. The first coat was allowed to dry; then a brass disk was painted with the same mixture and placed on the coated surface, thus insuring good contact, since the brass was held firmly after the ink had dried.

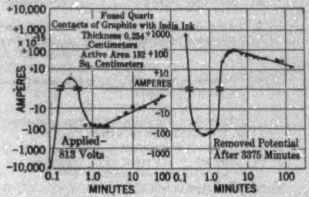

FIG. 12—FUSED QUARTZ WITH GRAPHITE CONTACTS

Figs. 11, 12, and 13 show typical sets of data taken with the new contacts. The reversals are shown very clearly. The relative magnitudes of the first and subsequent readings for each run are indicated best by Fig. 11, which is plotted using uniform scales. The same set of data is plotted for a much longer time in Fig. 12, using logarithmic scales. The effect of applying a negative instead of positive potential to $C_s$ is shown in Fig. 13.

In Figs. 12 and 13 the curves are broken where they cross the axis because the scales are logarithmic and no zero can be shown. So far as we could see, changing the contact surfaces did not affect the results, so that they indicate the reactions of the material itself. It is quite possible that in each case the observed results were preceded by unmeasured oscillations of much shorter period. As an aid in the possible interpretation of these results, the complete history of this sample of fused quartz, for two months preceding the final experiments, is tabulated in Table III.

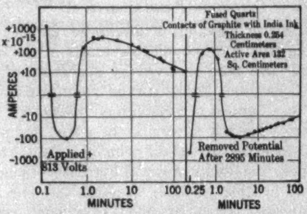

FIG. 13—FUSED QUARTZ WITH GRAPHITE CONTACTS

TABLE III

HISTORY OF PLATE OF FUSED QUARTZ

Previous to the tests recorded below the plate, with silvered surfaces connected together had been lying idle for some time. No residual charge could be detected

| Date | Days after 11/20 | Treatment | Remarks |
|---|---|---|---|
| 11/20/27 | 0 | Applied − 813 volts | Data plotted Fig. 9 |
| 11/22 | 2.1 | Removed potential | |
| 11/24 | 3.96 | Applied + 813 volts | Suspected erratic behavior at beginning |
| 11/25 | 4.98 | Removed potential | |
| 12/6 | 15.96 | Applied − 406.5 volts | Observed reversal during first minute |
| | 16.17 | Removed potential | |
| 12/7 | 17.1 | Applied + 406.5 volts | Observed reversal during first minute |
| | 17.35 | Removed potential | |
| 12/8 | 18.13 | Applied − 813 volts | Reversal observed but ordinates were not proportional to potential applied |
| | 18.35 | Removed potential | |
| 12/13 | 22.92 | Applied + 813 volts | Observed reversal |
| 12/14 | 24.12 | Removed potential | No data |
| 12/15 | 25.18 | Applied − 813 volts with 376 millihenrys in series | No apparent effect in results |
| | 25.22 | Removed potential | |
| 12/16 | 26.33 | Applied + 813 volts with same inductance in series | No effect |
| 12/17 | 26.92 | Removed potential | |
| 12/17 | 27.08 | Applied + 813 volts without series inductance | No effect |
| | 27.12 | Removed potential | |
| 1/ 9/28 | | Applied + 813 volts after plate had been grounded for three weeks | Data plotted Fig. 10 |
| | 50.19 | Removed potential | |
| 1/14 | 55 | Silver surfaces were removed and India ink with graphite contacts provided | |
| 1/18 | 59.1 | Applied + 813 volts | |
| 1/20 | 61.12 | Removed potential | Data plotted |
| 1/21 | 61.96 | Applied − 813 volts | Figures 11, 12, and 13 |
| 1/23 | 64.3 | Removed potential | |

*Reversals of Current in Fused Quartz.*

Reversals in direction of discharge current curves occurring after corresponding reversals of the charging potential have been observed by numerous investigators.[6] Richardson[8] shows curves demonstrating this effect for a sample of crystalline quartz cut parallel to the axis. The law governing the effect was stated in 1889 by Jacques Curie[1] as the principle of superposition.

However, the results shown in Fig. 10 to 13 cannot be explained by this principle because the specimen is kept grounded (short-circuited) after each test until it has relaxed as completely as it will; *i. e.*, until the upper plate shows no tendency to acquire a charge in either direction if the ground connection is removed. This is assumed to indicate a neutral or unstressed condition in the dielectric. Then, according to the principle of superposition, if a positive potential of constant magnitude were applied, the current flow would always be in the positive direction.

Perhaps, upon depolarization, the polarizing elements do not regain truly neutral positions, although they do assume an arrangement which is in stable equilibrium. Thus, the reversals observed might be caused by overstraining and slow time oscillation about a new equilibrium arrangement whenever the applied potential is changed.

This effect might be accounted for by the condition assumed at the point (6) of Fig. 12 in the recent paper published by Malti[7].

The writer is not prepared to offer any other explanation of the results observed, although he believes them to represent truly the reactions of the sample tested. He would be very pleased to learn whether other investigators have observed similar reactions on fused quartz or other materials.

TABLE IV

SUMMARY OF EXPERIMENTAL RESULTS

All data were taken at temperature of 20 deg.–22 deg. cent.

| 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| Hard rubber .... No. 7.......... | 200, 400<br>600, 800 | 6.5 by $10^{15}$ | 3.6 by $10^{18}$ | 550/1 | 0.924 |
| Hard rubber .... No. 5.......... | 400 | 1.7 by $10^{16}$ | 3.2 by $10^{18}$ | 190/1 | 0.953 |
| Pyrex glass...... No. 12........ | 200 | 4.9 by $10^{15}$ | 8.6 by $10^{16}$ | 17.5/1 | 0.6262 |
| Fused quartz.... No. 14........ | 3200 | 1 by $10^{18}$ approx. | 8 by $10^{19}$ | 80/1 | 0.678 |
| Crystalline quartz No. 11. | 1000 | 1 by $10^{16}$ | 1 by $10^{16}$ | 1/1 | 0.525 |

Column 1—material under test

Column 2—$G$ = applied potential gradient in volts/cm.

Column 3—$\rho_a = \frac{e}{i_1}$ = apparent resistivity where $i_1$ is the current per unit area in amperes/sq. cm. measured 1 min. after the application of potential

Column 4—$\rho_f = \frac{e}{i_g}$ where $i_1$ was the final constant value of $i$

Column 5—ratio of $\rho_a/\rho_f$

Column 6—coefficient $b$, when the polarization current is exressed by equation (1).

A compilation of the known characteristics of silica is presented by Sosman[12], "The Properties of Silica." However, no information similar to that observed by the writer was found in this work.

Crystalline Quartz cut Parallel to the Axis. A plate of clear crystalline quartz, cut parallel to the axis, was also borrowed from the Bureau of Standards. The contacts on this sample were made by sputtering a gold film in vacuum on the carefully cleaned surfaces. Here, again, a guard-ring was provided. The chief objection to this type of contact is the length of time necessary to get a good conducting film.

Fig. 14 shows the only set of data obtained to date on this sample. The upper curve shows that the final steady current is very high compared to that of fused quartz. The lower curve shows a return polarization current larger than the charging current for the first minute and a half, and continuing for an extremely long time. In fact, one month after the potential was removed, a discharge current could still be detected, although the plates had been short-circuited for the entire time. This indicates the difficulty of obtaining complete relaxation in such a material. The writer believes that if the charging current had been continued for 100,000 min., the lower part of the discharge curve might have continued a straight line instead of falling off as it did.

## SUGGESTIONS FOR FURTHER RESEARCH

### A. *Studies Similar to Those Reported Here.*

1. Studies on a large number of materials to separate them into the following three groups; (a) those showing both polarization and conduction; (b) those showing appreciable polarization and negligible conduction; (c) those showing negligible polarization and appreciable conduction.

For these studies, it would be necessary to keep constant the parameters listed below; but this would not require the apparatus necessary to vary them through wide limits, and therefore could be done much more easily.

2. Intensive study on a representative substance from each of the three groups listed above. To accomplish such a study, it would be necessary to control all of the variables which affect the phenomena. Then, by varying one at a time, keeping all the others constant, the individual effects of each parameter could be studied. This would be a large undertaking, require especially designed apparatus, and take a great deal of time. However, we cannot say much regarding dielectric reactions until it is accomplished. The possible parameters are: (a) thickness of specimen; (b) area of specimen; (c) temperature; (d) humidity; (e) potential gradient; (f) length of time of application of potential.

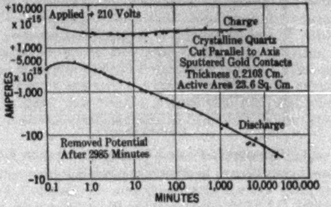

FIG. 14—CRYSTALLINE QUARTZ WITH GOLD CONTACTS

From this study a classification would be obtained separating dielectrics into two groups: (a) those whose reactions obey laws of proportionality with the possible parameters, and whose reactions can therefore be computed; (b) those whose reactions are quantitatively erratic and non-predictable.

### B. *Studies of Polarization Potential.*

The author believes that very interesting current-time relations will be found if, after a complete charge curve, the potential is reduced, not to zero as in the case of all the tests reported in this paper, but to a potential smaller than that previously applied and in the same direction. A family of such curves could be obtained by having identical charging conditions, and reducing the potential to different values, ranging from zero up to the potential applied during charge, (see Reference 8).

### C. *Studies of Residual Charge.*

If, after a complete charge curve, the condenser is short-circuited and then isolated, a difference of potential will gradually appear between the plates, showing that a free charge is collected on them which may be removed by again short-circuiting the plates. It would be very interesting to study this liberation of residual charge:

1. As a function of the time allowed between successive short circuits;

2. As a function of the rate of rise of potential which could be controlled by varying the capacitance of an air condenser placed in parallel with the specimen.

### D. *Studies of Energy Involved.*

1. Input Energy.

This may be computed by the equation

$$W_{input} = E_{CH} \int_0^d i_{CH}\, d\, t \qquad (4)$$

where $d$ is the time at which the charge is discontinued.

2. Recoverable Energy.

If experiments are performed as indicated under section $B$, above, and the value of the reduced potential $E_{DH}$ is such that current flows against this potential, the energy recovered is given by the equation:

$$W_{recovered} = E_{DH} \int_0^f i_{DH}\, d\, t \qquad (5)$$

where $f$ is the instant of time at which $i_{DH}$ reverses and begins to flow in the same direction as the previous charge current.

3. Loss to Heat.

The difference between the energy input and the energy recovered is energy lost. In all the experiments reported in this paper, the energy recovered was zero, since both plates of the condenser were maintained at zero potential during discharge. Therefore, all the energy input was lost to heat; (a), in forcing the material through the cycle of polarization, and (b), in the actual $I_o^2\, r$ loss. Therefore, the energy used in polarization could be computed by substracting from the input energy, the energy recovered, and the $I_o^2\, r$ loss, if we could assume that $I$ final $= I_o$.

### E. *Correlation of A-C. and D-C. Tests.*

As the frequency of the alternating potential is decreased, the loss per cycle ought to approach the loss per cycle of a d-c. test having the same magnitude of applied potential. Therefore, very interesting data should be obtained by using the same sample for both types of experiment and comparing the results.

## SUMMARY

A. A simple, sensitive modification of previous methods is developed for measuring current-time, charge and discharge curves in solid dielectrics with constant applied potential.

B. Coefficients of final apparent resistivity agree very well with those reported by earlier investigators. The fact that a higher value is reported for fused quartz is due to the extreme length of time taken, to allow the current to decrease to its minimum, and to the high sensitivity of the method of measurement.

C. The phenomenon studied must be due to some form of polarization, since representative curves were obtained with an insulating air-gap between the specimen and the upper plate of $C_s$.

D. 1. For all the materials studied, the law expressed by equation (**2**) is verified over a considerable length of time. An exception was found in fused quartz during the first minute or so after changing the applied potential.

2. The law expressed by equation (**3**) is verified for Pyrex glass and hard rubber.

3. For hard rubber within the range of potential studied, we have found that the polarization current is directly proportional to the applied potential, and that the relaxation coefficient $b$ in eq. (**2**) is independent of the applied potential.

4. The sample of fused quartz behaved differently from the other materials tested, and showed current reversals unaccounted for by the principle of superposition. Its reactions cannot be taken as representative of all dielectrics.

E. The final apparent resistivity of some materials can be determined only after a constant potential has been applied for several days; *i. e.*, it takes days, and even weeks, for $i_p$ to become negligible compared to $I_g$.

F. Of the several methods tried, India ink with finely powdered graphite was found to give the most satisfactory contact between the surfaces of the specimen and the brass plates of $C_s$.

### GENERAL CONCLUSIONS

A. Solid dielectrics showing the property of polarization may be found to divide themselves into distinct groups having entirely different conduction characteristics.

B. The mechanism of conduction in dielectrics differs from that in metals so that the expression "dielectric resistance" has an entirely different physical meaning from the expression "metallic resistance."

C. The present need in this field is for thoroughly coordinated, carefully executed researches to determine how *all* the related phenomena vary with changes of *all* the parameters which affect them.

## Bibliography

Extended biliographies on this subject will be found in references 6, 7, 10, 14, and 15. The others listed are simply those to which direct reference has been made in this paper.

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## Discussion

**C. L. Dawes:** I am particularly interested in work which involves the properties of dielectrics, since at Harvard University we are and have been for some time past conducting a similar study. In fact, P. L. Humphries, an instructor in Electrical Engineering, has already obtained the dielectric characteristics of Pyrex glass over a wide range of frequencies and temperatures. These results will be published in the *Electrical World* in the near future. Our special problem at present is the study of the ionization of gases. We restrict the energy flow to the gas with a slab of Pyrex glass, having an effective electrode area of 111.3 sq. cm. and a thickness of 1.411 cm. The characteristics of the gas are obtained by deducting the characteristics of the Pyrex glass from the measured characteristics of the glass and gas in series. It is, therefore, necessary to know the characteristics of the Pyrex glass. We first used ordinary plate glass, but later found Pyrex glass more suitable, because its characteristics vary much less with change in temperature. We attempted, without success, to obtain a suitable piece of fused quartz for this work.

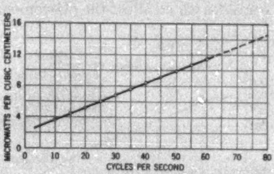

FIG. 1—FREQUENCY-POWER CHARACTERISTIC OF PYREX

3450 volts per cu. cm. gradient. Temperature—25 deg. cent.

In Fig. 1 herewith is shown a plot which gives the power loss of Pyrex glass as a function of frequency. The curve was obtained at 25 deg. cent. and with 5000 volts r. m. s. impressed, giving a gradient of 3540 volts per cm. The relation of power loss to frequency is linear. If the curve is extrapolated to zero frequency, the corresponding loss is 1.4 microwatts per cu. cm. This corresponds to $4.47 \times 10^{-9}$ watt per cu. cm. if the voltage gradient is 200 volts per cm. The watts loss per cu. cm. obtained by Professor Race with a gradient of 200 volts per cm. and at the final constant value of direct current may be obtained from Table IV and is equal to $(200)^2/(8.6 \times 10^{-16}) = 4.65 \times 10^{-13}$ watt. It is thus seen that there is a great difference between these two values. It does not seem possible that this difference can be accounted for by differences in the specimens tested.

It would have added considerably to our knowledge of dielectrics if it had been possible for us to obtain data between 20 cycles per second and zero frequency, and thus attempt to explain the above discrepancy. Addenbrooke[1] has made some comparisons of the d-c. characteristics of dielectrics with their a-c. characteristics. However, in our present research we are not particularly concerned with the Pyrex glass itself, but rather in the application of its dielectric characteristics to another problem. Hence, at this time we do not feel justified in carrying the research any further in this particular direction.

At first sight, it seems an anomaly that in the measurement of power loss, we are able to obtain far greater sensitivity with alternating current than with direct current, in spite of the fact that with alternating current, the energy component of the current is associated with a quadrature component having many times the value of the energy component. These two components must be separated in the power measurement. The reason that this high sensitivity is obtained with alternating current is that we are able to employ a very sensitive tuned galvanometer, working in conjunction with a vacuum-tube amplifier. Although we have an extremely sensitive d-c. galvanometer ($10^{-11}$ ampere for 1 mm. deflection at a distance of one meter) its sensitivity would need to be increased 1000 times to adapt it to the measurements of these samples of high-resistivity materials. Hence, some indirect method, such as is described in Professor Race's paper, is usually necessary Heretofore, very small currents such as electronic saturation currents, have been determined by measuring the change of potential across a condenser with some type of electrostatic instrument, often a gold-leaf electroscope. Professor Race eliminates the deflection errors, which are large in this type of instrument, by means of an electrostatic Poggendorff method. The instrument acts merely as a zero detector. From my own experience with this type of measurement, I agree with him that this null method has much greater inherent precision than the deflection method.

It is interesting to note that d- and a-c. losses in cables have been compared by Percy Dunsheath of the Henley Telegraph Works of England. He has found that for the same voltage gradient, the a-c. loss at 50 cycles varies from 13.4 to 3460 times the d-c. loss, depending on the temperature. ("Dielectric Problems in High-voltage Cables;" *Journal I. E. E.*, Vol. 64, 1925-26, page 113). At Harvard University we are making similar studies with cables and plan to publish some of the results.

We all realize that our present knowledge of the behavior of dielectrics is rather vague. The Committee on Dielectrics of the National Research Council and various committees of the national engineering societies are working to avoid unnecessary duplication in dielectric research and to correlate the results. The results of this paper, when correlated with similar work being carried on elsewhere in this country, should add to our knowledge of the behavior of dielectrics under the action of direct current.

**F. W. Grover:** I have been much interested in the paper by Professor Race because he deals with a subject on which I did some experimental work while at the Bureau of Standards. We studied what is called the absorbed charge of a condenser, that is, the charge that comes out of a condenser after it has been discharged and short-circuited for a while. In this study it seemed almost impossible ever to discharge a condenser. This is true of the best mica condensers which we used for standards at that time. In fact you might say that the condenser acted like a continuous, perennial source of energy.

But the thing that has interested me especially in the work of Professor Race is that a supposedly homogeneous substance like fused quartz should show this effect. That theory of dielectric absorption which has received the most attention and which has been regarded by most observers as offering an explanation for the *qualitative* phenomena, although perhaps not for the *quantitative*, is the law of stratified dielectric, brought out by Maxwell. According to that, it is a necessity with inhomogeneity of the dielectric that absorbed charges appear at the surfaces where the layers meet. But according to Professor Race a homogeneous substance also shows absorption. Some of the earlier investigators claimed that with substances believed to be perfectly homogeneous they found no absorption at all.

One observer, some ten years ago, working with thin layers of paraffine, claimed that if precautions were taken to insure the exclusion of air films, no absorption was found in this case also. The results obtained by Professor Race on fused quartz, on the contrary, although obtained with no chance for the presence of air films, show a well defined absorption effect.

I think this work is very instructive from the standpoint of dielectric theory.

**A. S. Dana:** I should like to ask Professor Race whether he thinks it is possible that the hard rubber showed the same phenomenon as the fused quartz (*i. e.*, the reversal during the first short period), but because the period was so short it escaped notice.

**H. H. Race:** In response to the last question, my object in this work was to obtain reliable quantitative data. Because the current changed very rapidly immediately after applying or removing potential, it was impossible to obtain quantitative data during the first minute. It was only in the case of fused quartz that unexpected reversals were observed and the apparatus changed so as to determine qualitatively at least the form of the current curve. In the case of hard rubber no such reversals were evident and no accurate data were sought during the first minute.

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[1] *Proc. Physical Soc. of London*, Vol. 27 (1915), p. 291.

# Interconnection of Power and Railroad Traction Systems by Means of Frequency Changers

BY LUDWIG ENCKE[1]

Associate, A. I. E. E.

*Synopsis.—Several types of variable ratio frequency-changers are discussed and installations of such apparatus on the electrified section of the New York, New Haven & Hartford Railroad are described in some detail.*

*These types of frequency-changers permit a flexible tie between interconnected systems, and accurate and automatic control of load regardless of variations in voltage or frequency in either system.*

*Any desired constant load transfer in either direction may be obtained through the apparatus by manually setting a load regulating relay. Provision is made also for operating the sets as synchronous condensers to improve power factor.*

*The functioning of regulating machines and auxiliary equipment to obtain the desired results is explained, together with a description of switching equipment installed in connection with the main units.*

A NUMBER of methods may be employed for connecting two power systems of different frequencies for interchange of power.

At the present time, a rigid tie by means of a synchronous motor-generator is common, and is in many respects the simplest form of connection. Since this rigid connection is wholly dependent upon both frequencies, it does not allow any regulation of the transferred load on the set itself. Furthermore the process of synchronizing is somewhat difficult, since for this purpose the frequency of one system or the other must be changed, and this of course can be done only at the power station. Another type of rigid tie which has been successfully employed consists (in the case for instance of a connection between systems of 60 and 25 cycle) of an induction machine, having a 60-cycle stator and a 25-cycle rotor, mounted on the same shaft with a 25-cycle synchronous machine. The slip-rings of the 25-cycle rotor of the induction machine are connected through a transformer, equipped with taps, to the 25-cycle system to which the synchronous machine is connected. This type of connection not only represents a power and frequency tie but also a voltage tie between the two systems.

A flexible connection is desirable in some instances, and obviously possesses fundamental advantages over any method of rigid tie, in that it permits not only merely tying together two power systems for interchange of power, but a close control of load as well. This may be of especial value in the supply of power for the operation of an electrified steam railroad extending over a large territory, from two or more central station generating plants located along the right-of-way at widely scattered points. In case of a single-phase electrified railroad, it may be necessary to change the 60-cycle power, available in most commercial power systems, into 25-cycle power necessary for traction purposes, at the same time operating in parallel with existing power plants owned by the railroad. By means of flexible connections any desired load distribution among different substations may thus be readily obtained, regardless of variations of frequency in any of the interconnected systems, all variations being absorbed in the machines themselves. Such flexible frequency-changer sets are known as "variable ratio" machines and usually consist of an induction machine, the speed of which is adjustable by means of auxiliary apparatus, mounted on a shaft with a synchronous machine. The speed regulating devices for the induction machine thus employed were originally designed for driving steel mills, etc., when variable speed was required. When used in connection with a frequency-changer set, the auxiliary apparatus usually consists of a three-phase commutator type machine with suitable exciting machines. Another method of obtaining the advantages of a flexible tie between power systems is the application of a rotary converter, (converting the alternating current of one frequency into direct current) in series with a second rotary converter "inverted," which in turn changes the direct current into alternating current of the other frequency. This method, however, is not in common use.

Recently a number of sets of the flexible frequency-changer type (motor-generator) has been purchased for use in connection with the New York, New Haven & Hartford Railroad's electrified system between New York and New Haven.

At present the single-phase 25-cycle system of the New York, New Haven & Hartford Railroad is fed mainly from the railroad's own power plant at Cos Cob, Connecticut. Power is supplied also from the Sherman Creek plant of the United Electric Light & Power Co. at New York. It has been found desirable with increasing loads to provide energy sources on the eastern end of the electric zone and connections have been made at New Haven with the 25-cycle system of the Connecticut Co., a subsidiary of the railroad operating the local street railway system, and at Devon, Connecticut, with the 60-cycle power system of the Connecticut Light & Power Co. In both instances, the connections are by means of "variable ratio frequency-changer sets," which are employed on account of the differences

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[1] Assistant Engineer, New York, New Haven & Hartford R. R. Co., New Haven, Conn.

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in frequency of the various systems involved, and for the ready control of the power. One unit has been installed in the power plant of the Connecticut Co. at New Haven and two units at Devon in a substation erected immediately outside the plant of the Connecticut Light & Power Co. All the sets are rated nominally at 5000 kw. A fourth set, a duplicate of the New Haven installation, has been installed in the Long Island Railroad's substation at East New York on the Bay Ridge line which has been recently electrified, together with the New York Connecting Railroad as an extension of the New Haven electrification system and receives its power from the New Haven supply. The East New York set is used normally as a rotary synchronous condenser, but is available for transferring power from the three-phase system of the Long Island and Pennsylvania Railroad to the single-phase system of the New Haven or vice versa, as a mutual standby.

Before describing the above mentioned installations in detail, a discussion of the general theory of the speed regulation of an induction motor may be of interest. The speed of an induction motor is fixed by the frequency of the power supply and the number of its poles. When a load is applied the rotor slips slightly, or loses speed. In order to obtain a regulation of the speed, resistance may be inserted in the rotor or secondary circuit of the motor. The current induced in the secondary circuit will thus decrease, and the result is a decrease of the torque and a consequent decrease of speed. Having reached a certain lesser number of revolutions, the current necessary for delivering the torque again flows in the motor's secondary on account of the increased slip voltage. Thus a certain amount of speed regulation of the motor may be obtained by inserting resistance in the rotor circuit. A disadvantage of this method is its lack of economy, since a part of the energy transmitted by the rotating field to the rotor is converted in the resistances into heat and is wasted. Furthermore, the speed regulation is not constant but changes with the torque or load on the motor and of course only regulation below synchronism is possible. Economical methods of regulation have been found in a number of arrangements. The slip energy of the induction motor may be transferred to an additional machine (the so-called regulating machine), where it may be transformed either into mechanical or electrical energy depending on the type of machine employed and thus utilized. By changing the excitation of the regulating machine a variable voltage is produced which, reacting upon the slip voltage, brings about the speed regulation of the induction motor.

The diagrams shown in Fig. 1 illustrate the speed regulation of an induction motor at speeds below synchronism.

Diagram A is the simplified diagram of an induction motor, disregarding reactance and the primary resistance of the machine.

$E_1$ is the primary voltage applied to the induction motor, producing in it the flux $\Phi$; for this purpose the magnetizing current $I_\mu$ is taken from the line or supply. $E_2$ is the voltage induced in the secondary of the motor and $I_2$ is the secondary current. $I_\mu$ and $I_2$ determine the primary current $I_1$ taken from the line.

In diagram B is indicated a counter voltage $E_{REG}$ introduced in the secondary of the induction motor. If the same torque is to be delivered by the motor, *i. e.*, if the same current $I_2$ flows through the rotor, the secondary or slip voltage must be increased to the new value of $E_2'$; thus the speed of the motor drops. $E_2' - E_{REG}$ results in the original secondary voltage $E_2$.

In diagram C it is seen that the regulating machine voltage $E_{REG}$ is not displaced by 180 deg. against $E_2$, but by a certain angle $\Theta$. This voltage $E_{REG}$ may be split up into two components. $E_R$ is the effective counter voltage; $E_x$ is the compensating voltage. The current $I_1$ is almost in phase with the primary voltage; thus power at nearly unity power factor is taken from the supply. The wattless current necessary for the excitation of the induction motor is delivered by the regulating machine due to the compensating voltage $E_x$.

As indicated above, three-phase commutator machines are used as regulating machines for the frequency-changer sets discussed herein. They may be mechanically coupled or driven separately. If the regulating machine is mechanically coupled to the induction motor, *i. e.*, installed on the same shaft or geared to it, it operates as a motor, assisting in driving the main shaft. A portion of the energy from the stator to the rotor of the induction motor is transferred mechanically to the main shaft and a portion is transferred electrically to the regulating machine, being transformed by the regulating machine into mechanical power. Disregarding the losses, the balance diagram is shown in Fig. 2. At any speed, a uniform horsepower is transferred to the shaft; in other words, the arrangement is a constant horsepower drive and the torque increases inversely in proportion to the speed. If, on the other hand, the regulating machine is mechanically separated from the induction motor it may be used to drive a separate machine, such as an induction generator. Only a part of the energy transferred to the rotor of the main induction motor is thus utilized in driving the main shaft, the rest being returned to the line through the regulating machine and induction generator. Dis-

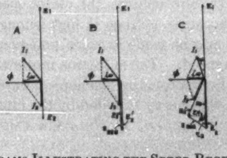


FIG. 1—DIAGRAMS ILLUSTRATING THE SPEED REGULATION OF AN INDUCTION MOTOR

regarding the losses the balance is indicated in diagram Fig. 3. This arrangement therefore represents a constant torque drive, the horsepower of which increases in proportion to the speed.

Thus far regulation only below synchronism, or full-load speed has been discussed. By adding auxiliary apparatus the induction motor may be regulated up to and above synchronism. It is, of course, practically always desirable in the case of variable ratio frequency changers that speed be controlled above as well as below synchronism.

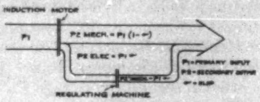


FIG. 2—BALANCE DIAGRAM FOR A CONSTANT HORSEPOWER DRIVE

A normal induction motor can reach practically synchronous speed only under no-load conditions. Its full-load speed lies slightly below synchronous speed. When the voltage of the regulating machine is reversed, thus raising the slip voltage, the motor speed increases, and if this boosting voltage is high enough, the speed of the motor may be made to reach, and even pass above, synchronous speed. The induction motor thus operates as a doubly fed motor, the mechanical output of which is the sum of the energy supplied by the line to its stator and the energy supplied by the regulating machine to its rotor. During operation at exactly synchronous speed the slip voltage, and thus the electrical energy transmitted by the rotation field to the rotor winding of the main motor being zero, the total secondary energy is delivered from the regulating machine, the necessary excitation of that machine being furnished by the above mentioned additional auxiliary apparatus. Above synchronism the direction of the slip voltage is reversed as compared to that of operation below synchronism. The resultant secondary voltage is again as in operation below synchronism the difference between the slip voltage and the voltage of the regulating machine. The secondary current, however, flows in the same direction. The relative directions of the voltage for speeds above and below synchronism are indicated in Table I, the directions for speeds below synchronism having been assumed arbitrarily. The tabulation shows clearly that the secondary current, as indicated, always takes the same direction, at speeds below synchronism as that of the slip voltage, and above synchronism as that of the voltage of the regulating machine.

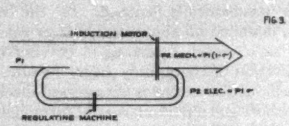


FIG. 3—BALANCE DIAGRAM FOR A CONSTANT TORQUE DRIVE

The speed regulating set in which the regulating machine is mechanically connected to the main shaft also operates at speeds above synchronism as a constant horsepower drive. The additional power taken by the induction motor from the supply line is used to drive the regulating machine, which thus operates as a generator.

TABLE I
DIRECTION OF VOLTAGE AND CURRENT IN THE MAIN INDUCTION MOTOR AND THE REGULATING MACHINE FOR SPEEDS ABOVE AND BELOW SYNCHRONISM

| | Below synchronism | | Between full-load speed and synchronism | | Above synchronism | |
|---|---|---|---|---|---|---|
| Machine | Voltage | Current | Voltage | Current | Voltage | Current |
| Ind. motor stator....... | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ |
| Rotor......... | ↑ | ↑ | ↑ | ↑ | ↓ | ↑ |
| Reg. machine commutator. | ↓ | ↑ | ↑ | ↑ | ↑ | ↑ |

The arrangement in which the regulating machine is mechanically separated from the main shaft is also a constant torque drive above synchronism. As the speed rises, the motor driving the regulating machine (*i. e.*, the induction generator now working as motor) takes increasing power from the line, which is supplied through the regulating machine to the secondary of the main induction motor.

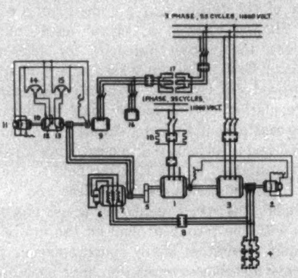

3 PHASE, 25 CYCLES, 11000 VOLT
1 PHASE, 25 CYCLES, 11000 VOLT
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

FIG. 4—DIAGRAM OF MAIN CONNECTIONS FOR THE FREQUENCY CHANGER SETS INSTALLED AT NEW HAVEN AND EAST NEW YORK

| | | | |
|---|---|---|---|
| 1. | synchronous machine | 10. | a-c. exciter machine |
| 2. | d-c. exciter | 11. | d-c. exciter |
| 3. | main induction motor | 12. | load field windings |
| 4. | secondary starting resistances | 13. | power-factor field winding |
| 5. | reduction gear | 14. | load field rheostat |
| 6. | polyphase regulating machine | 15. | power-factor rheostat |
| 7. | neutralizing windings | 16. | blower motor |
| 8. | tie breaker | 17. | auxiliary set transformer |
| 9. | synchronous driving motor | 18. | current limiting resistances |

Fig. 4 shows the wiring diagram of the frequency-changer sets installed in the New Haven and East New York substations. They consist of a main set and an auxiliary set. The main set is made up of a three-phase 25-cycle, 11,000-volt synchronous generator with d-c. exciter, a three-phase 25-cycle, 11,000-volt induction motor, the speed of which is determined by the synchronous generator, and the regulating machine which regulates the power flow of the set. The machines of the auxiliary set are, first a synchronous motor used for the drive, second a so-called a-c. exciter machine, and third a d-c. exciter, furnishing the excitation current for the other two machines. The induction motor, the synchronous generator, and the d-c. exciter of the main set are of standard design. The regulating machine is a rotor excited, neutralized a-c. commutator machine, the three-phase wound rotor having slip-rings and a commutator as in a rotary converter. Since the slip-rings carry alternating excitation current only, they are relatively small and the commutator segments are narrow, a feature of every a-c. commutator. The stator has a compensating winding which neutralizes the rotor field generated by the load current in the rotor, so that the machine can transform electrical energy to mechanical energy. The design of this machine is limited by the maximum permissible values of peripheral commutator speeds, the voltage between commutator bars and current densities, a satisfactory design thus requires that the kv-a. output per pole be somewhat limited, and it was desirable in order to obtain the required rating to build the machine at a slower speed than the main unit. The regulating machine, therefore, is connected to the main shaft through a reduction gear with a ratio of two to one and thus rotates at half the speed of the main set.

Fig. 5—Variable Ratio Frequency-Changer Set at Station "A," New Haven

In order to understand the operation of this machine, it may be assumed that the connections from its commutator brushes to the slip-rings of the main induction motor are cut off, and the slip-rings are connected directly to the line.

At stand-still a field will rotate with $n_1 = \dfrac{60\,\nu_1}{p}$ rev. per min. with regard to the stator and rotor, where

$\nu_1$ = frequency of the line

$2\,p$ = number of poles of the machine.

In rotating the rotor with $n$ revolutions opposite to the direction of the field, the resultant speed relative to the space will be:

$$n_1 - n$$

The voltage of the frequency $\nu_2 = \dfrac{p\,(n_1 - n)}{60} = s_2\,\nu_1$

is obtained at the brushes of the commutator, where

$s_2$ = slip.

The effective values of the voltages at the slip-rings and at the commutator brushes are practically equal. When $n_1 = n$, direct current appears at the brushes of the commutator. Therefore, if the regulating machine is given the same ratio of revolutions and number of poles as has the main induction motor, and the slip-rings are fed with line frequency, the slip frequency $\nu_2 = s_2\,\nu_1$ will always appear at the commutator brushes. Thus the commutator brushes of the regulating machine and the slip-rings of the main induction motor may be connected. As the voltages at the slip-rings and at the commutator brushes of the regulating machine are about the same, the latter, and thus the speed of the main set can be easily controlled by changing the voltage applied to the slip-rings of the regulating machine. It is a function of the auxiliary set to furnish to the slip-rings of the regulating machine this variable voltage at line frequency. The continuous delivery of line frequency is insured as the auxiliary set is a straight synchronous motor-generator, connected to the same line as the induction motor. The driving synchronous motor as well as the d-c. exciter are of standard design.

Fig. 6—Regulating Machine and Reduction Gear of the Main Machine Set at Station "A," New Haven

The a-c. exciter machine resembles an induction motor. Its field consists of three windings with a phase angle difference of 120 deg., two of which are connected in multiple. These windings independent of each other, excited by direct current, set up two fields which create a resultant field. The field of the two windings connected in multiple is the load field controlled by the load rheostat, whereas the field of the single winding is the power-factor field, 90 deg. out of phase with the load field, controlled by the power-factor rheostat. The load adjustment of the main set is obtained by changing the voltage generated in the a-c. exciter which is accomplished by varying the load rheostat, while the power factor of the main induction motor is adjusted by changing the power-factor rheostat which is of a potentiometer type. For running above synchronism the voltage of the regulating machine must be reversed; therefore the load rheostat is a reversing rheostat. Both the load and the power-factor rheostats are motor driven.

FIG. 7—AUXILIARY SET AT STATION "A," NEW HAVEN

The following frequencies appear on the various machines and their connections:

| | | |
|---|---|---|
| 1. | From line to stator of induction motor... | line frequency $\nu_1$ |
| 2. | In rotor of induction motor............. | slip frequency $\nu_2$ |
| 3. | From slip-rings of induction motor to commutator of regulating machine.. | slip frequency $\nu_2$ |
| 4. | From slip-rings of regulating machine to slip-rings of a-c. synchronous exciter.......................... | line frequency $\nu_1$ |
| 5. | From stator synchronous motor to line............................ | line frequency $\nu_1$ |

The regulating set works as a constant horsepower drive, as all the energy taken from the line is transferred into mechanical power on the main shaft, neglecting the losses in the machines.

As outlined above this variable ratio frequency-changer set represents an interconnection between two 25-cycle systems. If, however, the induction motor is a 60-cycle machine the excitation for regulation would also be 60-cycle. The inherent frequency is then higher, a condition which is not desirable with rotor excitation on so large a set. Some other arrangement is thus necessary. This condition may be taken care of by replacing the rotor excited regulating machine by a stator excited type.

A slightly different means of regulation known as the Scherbius system is employed in the installation at Devon. The same system may be applied to connections between two 25-cycle systems or between a 60-cycle and a 25-cycle system.

Figs. 8, 9, 10 show single-line wiring diagrams for various applications, as follows:

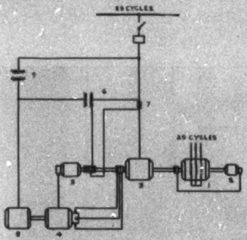


FIG. 8

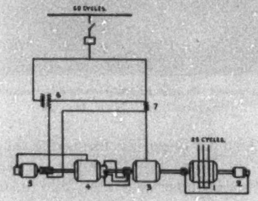


FIG. 9

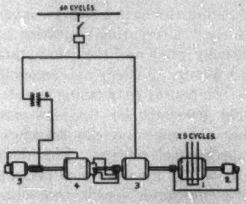


FIG. 10

FIGS. 8, 9, 10—SINGLE-LINE WIRING DIAGRAMS OF MAIN CONNECTIONS FOR SCHERBIUS CONTROLLED FREQUENCY CHANGER SETS

1. synchronous machine
2. d-c. exciter
3. main induction motor
4. regulating (Scherbius) machine
5. ohmic drop exciter
6. ohmic drop exciter transformer
7. bulging transformer
8. induction machine
9. power transformer

Fig. 8. Frequency changer suggested for a 25 cycle to 25 cycle tie.

Fig. 9. Frequency changer suggested for a 60 cycle to 25 cycle tie.

Fig. 10. Frequency changer 60 cycle to 25 cycle as in the substation at Devon.

These three wiring diagrams are perhaps especially interesting in their assemblage, in showing the progressive simplification.

Fig. 11 shows the three-line wiring diagram of the Devon set.

The frequency changer arrangement shown in Fig. 8 consists of a main and an auxiliary set. The latter includes the regulating machine and the induction machine, which at under synchronous speed operates as a generator driven by the regulating machine, and returns the slip energy back to the line. During operation above synchronism, however, the induction machine works as a motor and drives the regulating machine, which as a generator feeds the secondary of the main induction motor. The induction machine is of standard design. This set operates at a constant torque, while the arrangements shown in Figs. 9, 10, 11 show a constant horsepower drive, as the regulating machine is mounted on the main shaft.

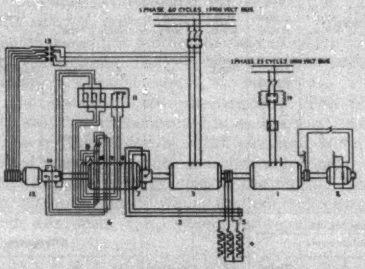

3 PHASE, 60 CYCLES, 13200 VOLT BUS
3 PHASE, 25 CYCLES, 11000 VOLT BUS
13
11
14
10
12
7
3
1
2
6
3
5
4

FIG. 11—DIAGRAM OF MAIN CONNECTIONS FOR THE FREQUENCY-CHANGER SETS INSTALLED AT DEVON

1. synchronous machine
2. d-c. exciter
3. main induction motor
4. secondary starting resistances
5. contactors
6. regulating (Scherbius) machine
7. neutralizing windings
8. power-factor control field windings
9. interpole field windings
10. load control field windings
11. power-factor rheostat
12. ohmic drop exciter
13. ohmic drop exciter transformer
14. current limiting resistances.
A & B contactors
15. movable brushes

The synchronous generator, its d-c. exciter, and the main induction motor have no unusual features. Common to these regulating sets and resembling in appearance a d-c. machine is the Scherbius regulating machine. Like a d-c. machine, it has main poles and interpoles. The excitation, however, is alternating current instead of direct current. As the frequency of the excitation voltage determines the frequency at the commutator brushes which are connected to the slip-rings of the main induction motor, the regulating machine must be excited with slip frequency. Furthermore, the voltage existing at the commutator brushes, and thus the speed of the regulating set, is controlled by varying the excitation voltage.

This excitation voltage is furnished from the line through a special auxiliary machine known as an ohmic drop exciter or frequency changing exciter which works as a frequency converter. Its operation resembles that of the regulating machine previously described. The rotor is analogous to the rotor of a rotary converter in that it is three-phase wound, and has slip-rings as well as a commutator. The stator has no field winding, and is merely a laminated steel ring to provide a flux path. The slip-rings are connected through a transformer to the line. Since it is mechanically coupled to the main induction motor and has the same number of poles, a voltage of slip frequency exists at its commutator brushes, which is employed for the excitation of the regulating machine. The commutator carries two sets of brushes which are moved by a brush-shifting device, and the regulation of the excitation voltage is accomplished by shifting these brushes. That is, by moving the brush-shifting device in one direction or the other, more or fewer commutator bars are included between the brushes, and the excitation voltage applied to the regulating machine is thus raised or lowered. The brush-shifting device provides for operation at under synchronous as well as above synchronous speed by reversing the excitation voltage. Two contactors *A* and *B* are provided in the connections between the ohmic drop exciter and the regulating machine. During under synchronous operation as well as at synchronous speed contactor *B* is closed, connecting the ohmic drop exciter to the Scherbius machine through its interpoles, whereas above synchronous speed the contactor *A* is closed, connecting the ohmic drop exciter directly to the Scherbius machine.

As in the regulating sets of other types, these sets also are equipped with apparatus to correct the power factor of the main induction motor. As shown in the wiring diagram Fig. 11, the so-called power-factor rheostat is connected in series with the load control field windings of the regulating machine. The degree of lag of the exciting current behind the voltage can be varied in changing the resistance of these windings by means of the rheostat. The regulating machine is equipped in addition with separate power-factor control windings, which are used when no excitation is supplied to the load control field circuit, the first method described for power factor correction being under these conditions ineffective. These separate power-factor control windings are connected from one set of brushes through a second section of the power-factor rheostat to a star point. The voltage supplied to the power-factor control windings is constant and about in quadrature to that of the load control field. As the excitation in the load control windings is increased, the effect of the power-factor control windings is reduced. Before the application of the automatically controlled power-factor rheostat, which is described below, was contemplated, an additional apparatus for power factor correction known as a "bulging transformer" together with a manually operated power-factor rheostat was considered. As shown in the wiring diagrams Figs. 8 and 9, the ohmic drop exciter is fed by its line transformer through the secondary of the bulging transformer, while the stator current of the main induction motor (fed from the line) flows through the bulging transformer primary. The voltage induced in the secondary of the bulging transformer (varying with the load on the induction motor) and the voltage furnished by the ohmic drop exciter transformer, are out of phase, and when combined obviously create a resultant voltage. This resultant voltage applied to the slip-rings of the ohmic drop exciter, changes automatically with the load. Additional control is accomplished in this case, as indicated above, by means of a manually instead of an automatically operated power-factor rheostat. Both brush-shifting device and power-factor rheostat are motor operated.

TABLE II

TECHNICAL DATA SPECIFIED FOR THE VARIOUS FREQUENCY-CHANGER SETS

| A | Frequency | | Regulation per cent | No load speed | | Generator kv-a. | D-c. exc. kw. | Ind. motor hp. | Reg. mach. kv-a. | Ind. mach. kv-a. | Ohm. Dr. exc. kv-a. | Syn. motor kv-a. | A-c. exc. kv-a. | D-c. exc. kw. | Reg. machines | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | mot. | gen. | | Main set | Aux. set | | | | | | | | | | No of r. mach. | Total kv-a. of reg. mach. | |
| A | 25 | 25 | 6 | 750 | 750 | 7140 | 85 | 7200 | 450 | .. | .. | 45 (60 hp. 100% pf.) | 150 | 16 | 4 | 661 | Installed at New Haven |
| B | 25 | 25 | 3 | 500 | 750 | 7140 | 85 | 7100 | 250 | 325 | 5 | .. | .. | .. | 3 | 580 | |
| C | 60 | 25 | 8.4 | 500 | .. | 7140 | 90 | 7200 | 500 | .. | 45 | .. | .. | .. | 2 | 545 | Installed at Devon |

| B | System frequencies | Weights in pounds | | | | | | Dimensions | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Main-set | | Auxiliary-set | | |
| | | Generator | D-c. exc. | Ind. motor | Bearings & accessories | Reg. mach. | Total | Length in. | Width in. | Length in. | Width in. | Total sq. yard |
| A | 25 to 25 | | | | | | | 726 | 143 | 139 | 60 | 86.5 |
| B | 25 to 25 | 192,000 | 4000 | 90,750 | 39,000 | 24,900 | 350,650 | 443 | 180 | 131 | 67 | 68.3 |
| C | 60 to 25 | 192,000 | 4000 | 61,000 | 50,000 | 29,000 | 336,000 | 579 | 188 | .. | .. | 84.0 |

| | System frequencies | Efficiencies | | | |
|---|---|---|---|---|---|
| | | ½ load % | ¾ load % | 1/1 load % | 1¼ load % |
| A | 25 to 25 | 82.7 | 86.6 | 88.1 | 87.7 |
| B | 25 to 25 | | | 88.0 | |
| C | 60 to 25 | 80.3 | | 86.9 | 88.0 |

All of the regulating sets discussed above are started from the induction motor side of the main set by inserting resistances in its secondary. When an auxiliary set is used, it is connected to the line at the same time or shortly before the main set. After the induction motor has reached its full speed, its secondary slip-rings are connected to the commutator of the regulating machine; thus, the load which is to be transferred and the power factor of the main motor may be adjusted. Full automatic starting of the sets has been provided in all cases.

The synchronous generators furnishing the single-phase railroad power are built as three-phase machines, having the single-phase rating as shown in Table IIA. The stators are all spring mounted, in order to reduce vibration due to the single-phase load. These springs are installed on both sides of the stators which are thus entirely supported by them. Leaf springs are used at New Haven and East New York, while at Devon, helical springs are employed.

All installations are equipped with automatic load regulators which, when adjusted for any given kw. value, provide that during all variations of frequency in the interconnected systems, within the allowed limits as described below, the transferred kw. load shall remain constant. Two different types of load regulators are used; in the New Haven and East New York substations a rheostatic type is installed, while those in the Devon substation are of a polyphase induction type.

The rheostatic type load regulator has as a control element two solenoids, one of which carries a current and a voltage coil, energized from a current and a potential transformer in the single-phase generator circuit, and connected in such a way, that its pull is proportional to the single-phase kw. load. The plunger of this solenoid acts on a lever arrangement, which carries a double acting circuit closing contact. The second solenoid which is energized through two d-c. coils acts on the same lever arrangement to prevent hunting. A variable anti-hunting rheostat is also connected into the circuit of one d-c. winding. Two dash pots stabilize the operation of the control element, and the pull of the alternating current aided by counterweights balances the weight of the core. A variable rheostat, a so-called load adjusting rheostat, is connected in parallel to the current coil of the a-c. solenoid. By means of this rheostat, more or less current can be shunted through the a-c. coil, and various values of kw. load can be obtained by means of a calibration dial which is graduated in terms of kilowatts. The load regulator is in equilibrium for a given kw. value dependent on the position of the load adjusting rheostat. As soon as the output of the single-phase machine varies, this equilibrium is destroyed and the double acting contact mentioned above will close in one or the other direction. Two reversing contactor switches are provided and are energized over the main contact of the control element. If the load drops below the value for which the regulator is set, the main contact closes, energizing one of the reversing contactor switches, which in turn allows the current to flow through the armature of the motor driving the load rheostat and turning it in the "raise" direction. If the load increases above the value as fixed by the setting, the other reversing contactor switch is energized resulting in the rotation of the rheostat driving motor into the "lower" direction. The motor is a shunt motor, the field of which is permanently energized. The reversing contactor switches have two additional contacts, which are closed when the switches are deenergized. The motor and the switches are connected in such a way that the armature of the motor is short circuited when the additional contacts of both switches are closed. The dynamic braking, thus applied to the motor, stops it almost instantaneously when the control element's contacts are open, *i. e.*, when the regulator is in equilibrium.

Fig. 12—Variable Ratio Frequency-Changer Sets in the Substation at Devon

The polyphase induction type load relay as installed at Devon is similar in its construction to a polyphase watthour meter. The relay has two stationary electromagnetic elements consisting of a current winding and a potential winding with laminated steel magnetic circuits. These windings are energized from a current and a potential transformer in the three-phase induction motor circuit and the two elements react on two disks on a single vertical shaft. They are suspended from a torsion wire and operate a double throw circuit closing contact. Two permanent magnets are used to damp the rotation of the disks. The torsion wire balances against the pull of the elements and its tension can be manually changed. For this purpose a knob and a scale graduated in kilowatts are provided, allowing the setting of the relay for each desired kw. value within the capacity of the machine set. As soon as the load varies from the value for which the relay has been set the double throw main contact closes. This energizes by means of an instantaneous auxiliary relay the "raise" or "lower" relay, which in turn closes the armature circuit of the motor driving the brush-shifting device on the ohmic drop exciter in one direction or the other. These latter relays have also additional contacts, which are closed in order to permit dynamic braking, when the relays are deenergized. The armature of the motor, (which in this case is a series motor), is short-circuited when these contacts of both relays are closed, while the series field winding of the motor remains energized over an inserted resistance.

Fig. 13—Secondary Starting Panel and Resistances, and Power-Factor Rheostat in the Substation at Devon

In all the substations, the load regulation of course can be performed manually as well as automatically. In the case of the New Haven and East New York substations a two-position control switch is provided to accomplish these two modes of operations, while at Devon, a control switch for the manual operation and a transfer switch for changing to automatic control are installed. The technique of placing the machines under the control of the automatic regulators is very simple in all the installations. After the generator is synchronized with the railroad power system, the control switch or the transfer switch is placed in its "regulating" position and the load adjusting rheostat at New Haven and East New York and the knob of the load relay at the Devon substation are adjusted slowly until the pointers indicate on the scale the load which it is desired to carry.

All frequency-changer sets under discussion can of course fundamentally transfer power in either direction; nevertheless only the sets at New Haven and East New York are specifically intended for interchange of power, the installation at Devon being arranged to transfer power only from the 60-cycle system to the 25-cycle system.

The range of the frequency regulation of the sets is shown in Table IIA.

The regulating sets installed at the New Haven and East New York substations (Fig. 4) and at Devon (Fig. 11) as mentioned above are constant horsepower drives. In the design of speed control for steel mill motors the decision as between a constant horsepower or a constant torque drive is determined by local operating conditions. This does not apply to frequency changers, and either form of drive may be applied. Nevertheless the demands of a frequency changer are of course more those of merely a constant horsepower drive. When the machines are once adjusted for a given load the transferred horsepower must remain constant independent of frequency (*i. e.*, speed variation) in either or both of the two systems connected. It is to be noted that a constant horsepower drive, as has been pointed out, involves one auxiliary machine less than a constant torque drive.

Table II contains technical data of interest in connection with the various sets discussed.

Having considered the different types of variable ratio frequency changer sets, it may be of interest to note briefly the general layout, the switching equipment, the protective devices, and the operating conditions of the machine sets installed in the two substations at New Haven and at Devon.

The variable-ratio frequency-changer set at New Haven has been installed as an interconnection between the systems of the N. Y., N. H. & H. R. R. Co. and of the Connecticut Co., in the power plant of the latter company at New Haven, Connecticut, which is known as Station A. The existing power plant building has been extended one bay and the main set is installed on the operating floor, with the auxiliary set on the main floor below. A mezzanine platform was erected on the steel foundation of the main unit, between the main and the auxiliary sets, for the secondary resistances of the main induction motor, the load and power-factor rheostats and the tie breaker. The switching equipment and the switchboard are built as extensions to the existing equipment of the Connecticut Co. and conform as far as possible to existing conditions. All operations for starting and operation of the set are controlled from the switchboard. The main induction motor is designed for forced ventilation by means of a motor-driven fan. The bearings of the main set are water-cooled and self lubricating.

Fig. 14 shows a wiring diagram of the machine set and indicates the instruments and protective devices used. The automatic protection of the set includes the protection of the various machine units and the means to secure the proper starting sequence. The main induction motor as well as the generator is equipped with differential relays to protect against internal faults. For the protection of the synchronous generator against excessive overload, especially when operating as a condenser, the voltage regulator is provided with a device for limiting the field current. The auxiliary set together with the blower motor is fed through fuses from the 440-volt auxiliary busses of the power plant.

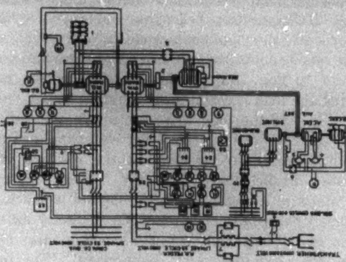


FIG. 14—WIRING DIAGRAM OF FREQUENCY-CHANGER SUBSTATION AT NEW HAVEN

1. secondary starting resistances
2. tie breaker (oil circuit breaker)
3. reduction gear
4. load field rheostat
5. power-factor rheostat
6. field transfer switch
7. current limiting resistance
8. differential protection relay
9. emergency overload relay with a high time setting
10. overload relay used for controling the operation of the oil circuit breakers shunting the current limiting resistances
11. voltmeter
12. ammeter
13. wattmeter
14. watthour meter
15. reactive volt ammeter
16. power-factor meter
17. frequency meter
18. synchronoscope
19. graphic voltmeter
20. graphic ammeter
21. graphic wattmeter
22. voltmeter switch
23. ammeter switch
24. load regulator
25. load adjusting rheostat
26. voltage regulator
27. power-factor regulator
28. auto transformer feeding the accelerating relays
29. auxiliary switch of tie breaker, shown in open position of tie breaker

A number of interlocking devices provides a proper starting sequence. The starting of the set is possible only when the load field rheostat and the power-factor rheostat are in their neutral positions, to which they are brought manually. Furthermore the tie breaker connecting the slip-rings of the main induction motor to the commutator brushes of the regulating machine must be opened. For this purpose, this breaker is interlocked with that of the main induction motor in such a way that tripping the latter trips the tie breaker automatically. An interlock between the breaker of the auxiliary set and the main induction motor breaker insures that when one trips the other one is tripped automatically. The load and the power-factor rheostats being in proper positions, the closing of the control switch of the main induction motor breaker opens the starting sequence. The secondary resistances of the main motor are short-circuited step by step, as controlled by accelerating relays, which allow the short-circuiting of the next resistance step only after the primary current is lowered sufficiently. At the same time, the auxiliary set and the blower motor start. Full voltage is applied to the stator of the synchronous driving motor of the auxiliary set (which is provided with a damper winding), and its field is short-circuited over the field discharge resistance. After reaching full speed and after building up the voltage of the d-c. exciter of the auxiliary set, the discharge circuit is opened and the field is connected to the d-c. exciter machine, and the tie breaker closes. The speed regulation can now be applied by manipulating the load-field rheostat, facilitating the synchronizing of the generator with the railroad supply. The blower motor is a squirrel-cage motor, which is started with full voltage and speeds up to its constant speed. The set is now ready to supply power from one system to the other.

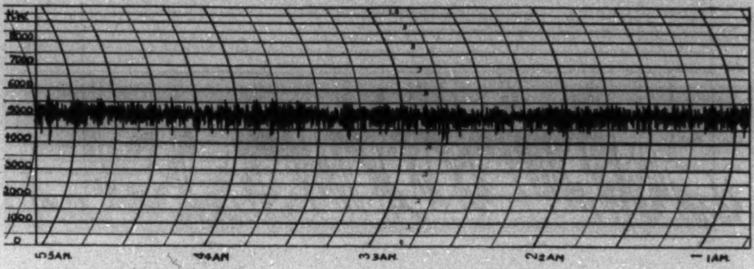


Fig. 15—Kw. Load on the Frequency-Changer Set at New Haven

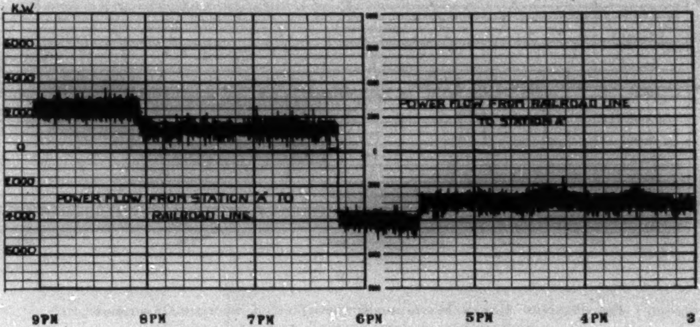


Fig. 16—Kw. Load Curve for Power Flow in Both Directions

Typical for every single-phase railroad load are the heavy and sudden swings of the load in kilowatts as well as the reactive kv-a. load. Nevertheless, in putting the machine under the control of the automatic load regulator, a given kw. load representing a base can be accurately maintained, while the swings are taken up by another source of supply. Any desired load within the capacity of the machine can thus be adjusted. Fig. 15 shows such a kw. curve; in this instance the automatic load regulator was adjusted for a value of 5000 kw., and it is of interest to note how the load was kept constant within comparatively narrow limits, in spite of the widely varying system load.

As previously mentioned the sets at New Haven and East New York have been arranged for power flow in both directions. Fig. 16 shows such an operation.

The sets at New Haven and at Devon as well as that at East New York are operated part of the time as motor-generators and part as synchronous condensers. It is obvious that when running as a synchronous condenser, a constant wattless output cannot be sustained if the voltage is to remain constant. The wattless output of lagging current or in other words the wattless input of leading current is carried by the machine as may be necessary; that is, the machine performs the function of keeping up the line voltage by putting out wattless current to take care of the wattless load. During such a period, the power plant at Cos Cob, of course, shows a power-factor improvement. But as soon as the which, as soon as the machine is overloaded, reduces the voltage and in doing so the wattless current carried. Safe operation as a rotary condenser without this current-limiting device would be difficult. Figs. 17A and B show the operation of the machine at New Haven as a synchronous condenser under normal conditions. A represents the amperes carried and B the voltage. Figs. 18A and B represent also synchronous condenser operation but under unusually severe load conditions. The ampere curve is of interest on account of showing the highly swinging wattless load; the influence of the "moving" wattless load is in the vicinity of Cos Cob, the wattless current is furnished from there, and the synchronous condenser at New Haven thus runs more or less idle. Obviously, it would be impossible to keep constant the reactive kv-a. load of the synchronous condenser, since the voltage regulator is set for maintaining voltage at a desired value and tends to keep this voltage constant by varying the excitation of the machine; that is, for carrying varying reactive kv-a. load. It is for this reason, as above stated, that the regulator is equipped with a current-limiting device, current-limiting device can be recognized very clearly in the voltage curve.

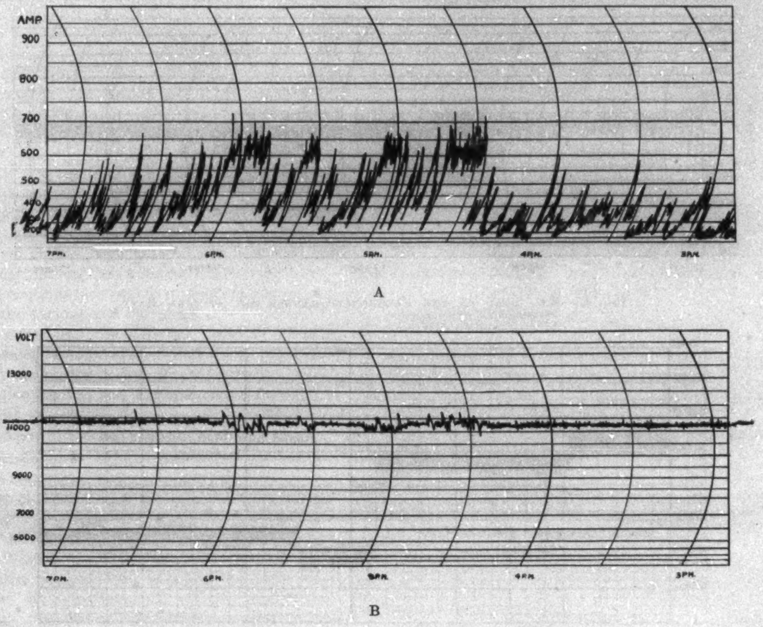
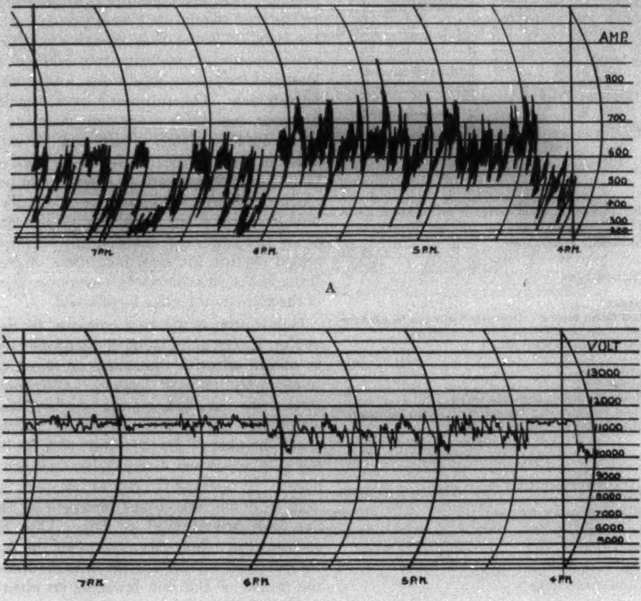


FIG. 17—NEW HAVEN MACHINE, RUNNING AS SYNCHRONOUS CONDENSER

*a* = current *b* = voltage at terminals

At Devon, Connecticut, where is located the interconnection between the systems of the N. Y. N. H. & H. R. R. Co. and of the Connecticut Light & Power Co., a substation building was erected outside the power plant for housing the frequency-changer sets and their associated equipment. The two machine sets are installed on the main floor, and the auxiliary equipment, such as secondary starting panels and resistances for the main induction motors, the various rheostats, and the transformers for the ohmic drop exciters, in the basement. A special room is provided for the switchboard. Outside of the building on one side are the 60-cycle busses, transformers, oil circuit breakers, and the incoming feeders, while on the opposite side are located the 25-cycle busses, transformers, and outgoing feeders to the railroad system. The substation is operated by the Connecticut Light & Power Company.

All machines are self ventilated. The single-phase generators, as above stated, may be operated as synchronous condensers. The bearings are water-cooled and self lubricating during running; during starting, however, an oil pump supplies oil under pressure to lift the rotating element from the bearings in order to reduce the break-away torque.



A

B

Fig. 18—Synchronous Machine at New Haven, When Running as a Synchronous Condenser Under Unusually Heavy System Load Conditions

*a* = current *b* = voltage at terminals

Fig. 19 shows the wiring diagram indicating the instruments and protective devices used. Here, too, the main machines are protected by differential relays against internal faults. In addition the induction motor circuits are equipped with overload relays. The ohmic drop exciters also have overload protection, which operates to open the main breakers, thus shutting down the whole set. The synchronous generators are protected against excessive overload by a current limiting relay connected to the voltage regulators. Before starting, the power-factor rheostat is in its "all in" position and the brushes of the ohmic drop exciter in their neutral position, having been brought to these positions automatically when the set was shut down.

These sets are started automatically by simply closing the main induction motor circuit breaker. The secondary resistances of the induction motor are short circuited step by step, as controlled by timing relays, which allow the short-circuiting of the next resistance step only after a certain given time, the steps in this instance not being a function of current. The final connection between the slip-rings of the main induction motor and the commutator brushes of the regulating machine is performed by contactors as the last step of the starting sequence.

Normally one set only is operated either as a tie or as a synchronous condenser, the other one being held as a spare unit except in emergency. Fig. 20 shows a kw. curve, when the machine is under the control of the automatic load regulator. This curve is of interest in comparison with Fig. 21, which shows the typical variation of the kw. output of the power station at Cos Cob to the eastern part of the line. Figs. 22A and B show the ampere and the voltage curves, when operating as a synchronous condenser. As stated previously, the automatic load regulator in the case of the New Haven set is controlled by the single-phase output of the synchronous generator, whereas the automatic load regulator of the Devon set is inserted in the three-phase circuit of the main induction motor.

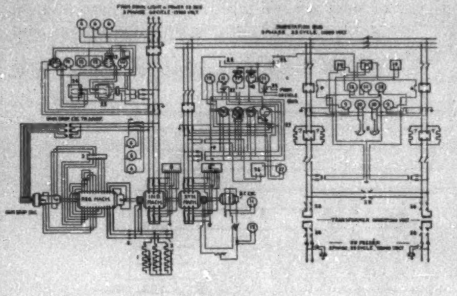


Fig. 19—Wiring Diagram of Frequency-Changer Sets and the Outgoing Railroad Feeders of the Substation at Devon (One Set Only Indicated)

1. secondary starting resistances
2. contactors
3. power-factor rheostat
4. auxiliary switch of feeder breaker. Only one feeder can be used for supplying power to the railroad system at the same time
5. adjusting rheostat for overload relay No. 10
6. overload relay
7. current limiting resistance
8. differential protection relay
9. emergency overload relay with a high-time setting
10. overload relay used for controling the operation of the oil circuit breakers shunting the current-limiting resistances
11. voltmeter
12. ammeter
13. wattmeter
14. watthour meter
15. reactive volt ammeter
16. power-factor meter
17. frequency meter
18. synchronoscope
19. graphic voltmeter
20. graphic ammeter
21. graphic wattmeter
22. V. M., Fr M., synchronoscope plug
23. A. M. jack
24. load regulator
25. power-factor regulator
26. voltage regulator
27. current limiting relay for voltage regulator
28. horn gap switch

All frequency-changer sets are equipped with automatic reactive kv-a. regulators for the main induction motor. They are similar in construction and operation to the load regulators already described. The regulator installed in the New Haven substation maintains a power factor of approximately 100 per cent under all load and frequency conditions, and does not allow any adjustment. The automatic kv-a. regulator at Devon, however, maintains a constant reactive kv-a. value of the induction motor, which can be adjusted to any value in such a way that for every load setting a power factor up to 90 per cent or even to 100 per cent may be reached. These automatic kv-a. regulators are desirable to increase the simplicity of operation, inasmuch as in the course of maintaining a constant predetermined load on the sets, regardless of frequency variations in the interconnected systems, the power factor of the main motors may be affected.

One feature of interest common to the installations at New Haven and Devon is the protective arrangement to obtain selective operation on short circuits on the single-phase railroad system. Current-limiting resistances are installed on the single-phase ends of the machines, which are normally short-circuited by circuit breakers. In the event of a fault or ground on the railroad system, these resistances are automatically inserted by opening the circuit breakers, after which the local sectionalizing circuit breakers on the line feeding the fault are allowed to trip. The resistances are automatically short-circuited after the faulty section is cut out, and normal operation is resumed. In case of the failure of the line breakers to clear the line, the whole substation is separated from the railroad line after a predetermined time by the opening of the main circuit breakers.

The installations at Devon and New Haven were

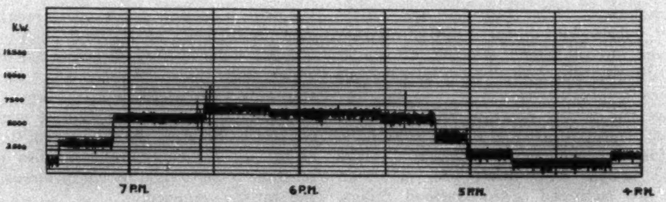


Fig. 20—Kw. Load on the Frequency-Changer Set at Devon

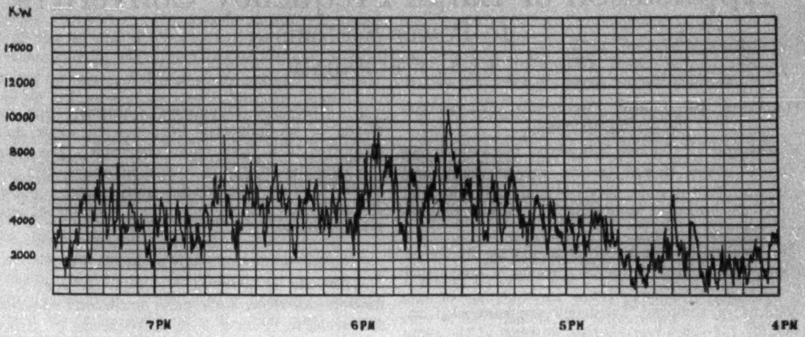
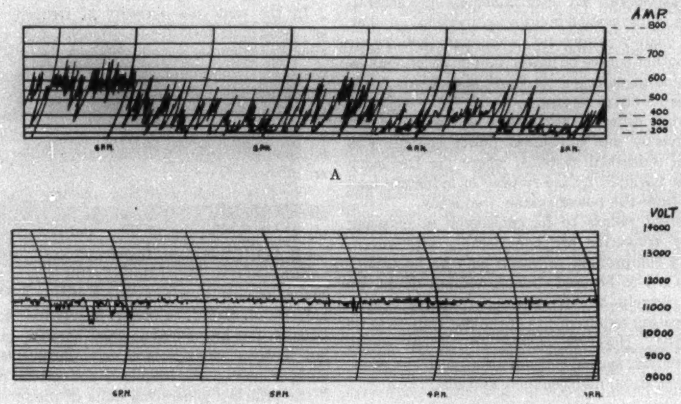


FIG. 21—KW. LOAD CURVE OF THE POWER STATION AT COS COB, CONTEMPORANEOUS WITH CONDITIONS SHOWN IN FIG. 15



A

B

FIG. 22—SYNCHRONOUS MACHINE AT DEVON, RUNNING AS SYNCHRONOUS CONDENSER

*a* = current *b* = voltage at terminals

made under the general direction of Sidney Withington, Electrical Engineer of the New York, New Haven & Hartford Railroad, H. F. Brown, Asst. Electrical Engineer, and the writer. That at East New York was under the general direction of L. S. Wells, Electrical Superintendent of the Long Island Railroad. Messrs. Gibbs & Hill, New York, acted as consulting engineers for all the installations.

## Discussion

For discussion of this paper see page 1079.

# Application of Large Frequency Converters to Power Systems

BY E. J. BURNHAM[1]

### APPLICATION OF LARGE FREQUENCY CONVERTERS TO POWER SYSTEMS

IN selecting a frequency converter, there are many things which should receive special study and consideration in order that the equipment obtained will meet the necessary requirements in the best possible way.

The purpose of this paper is to discuss frequency converter sets and their use as a means of connecting systems of different frequency.

Systems of different frequency are connected together for the same reasons that systems of the same frequency are connected; namely, to save capital investment in generating equipment, and improve service to customers. By interconnection, the generating capacity of one system is made available for another, which may mean a large total saving and furthermore provides another source of power supply which may be of great value in emergencies when stations or transmission lines are out of service.

A somewhat different application is the use of frequency converter sets to connect power systems with railway and industrial systems, where the frequency of the power required by the railway or industrial load is different from the power system frequency.

The different points to be considered in choosing a frequency converter are considerably interwoven, so at best a compromise selection may be necessary. The type of set to be used should, without doubt, be determined largely by the particular characteristics and the operating requirements of the two systems to be interconnected. However, there are other points which may require special consideration, such as design, efficiency, operation, maintenance, and cost.

### TYPES OF FREQUENCY CONVERTERS

The following types of frequency converters will be considered:

1. Synchronous-synchronous type, consisting of a synchronous motor direct-connected to a synchronous generator.
2. Induction-synchronous type, consisting of an ordinary induction motor direct-connected to a synchronous generator.
3. Adjustable-ratio induction-synchronous type, consisting of a wound rotor induction motor direct-connected to a synchronous generator, the induction motor having suitable control equipment to give a variable frequency ratio between the two systems to be connected together.
4. Fixed-ratio induction-synchronous type, consisting of an induction frequency converter direct-connected to a synchronous generator. The rotor of the induction motor is connected electrically to the stator of the synchronous unit, thereby allowing electrical, as well as mechanical transfer of power through the set.

### SYNCHRONOUS-SYNCHRONOUS TYPE

With the synchronous-synchronous type of frequency converter, both units necessarily operate in synchronism, forming a rigid frequency tie between the two systems connected together. Therefore, with this type of set, the ratio between the frequencies of the two systems must normally remain constant.

In the past, the majority of frequency converter sets used have been of the synchronous-synchronous type because such sets are adaptable to simplicity of design and operation and may have low costs, high efficiency, and ability to correct power factor. Sets of this type can be sturdy and simple in design and have a minimum number of auxiliary parts. This results in minimum attention and low maintenance costs, which are important points.

The power factor of either machine may be conveniently adjusted by field control. Furthermore, if the set is not being used as a tie, either machine may be used as a synchronous condenser.

The load transferred through this type of set must be controlled by governor adjustments on the prime movers of either or both interconnected systems. Usually, this introduces no great hardship in operation, but in some cases it is a very inconvenient way of holding load on the frequency converters, particularly if the principal generating units of the interconnected systems are controlled by other companies.

In case it is desirable to synchronize the two systems at a frequency converter station, the governors of the prime movers must be adjusted until synchronizing can be accomplished. This again may be inconvenient, as it usually means telephoning to some distant generating station.

In using a frequency converter set of the synchronous-synchronous type, the capacity of the set may be determined by the size of the set that will reasonably hold the two systems together, rather than by the size of set required to transfer the amount of power desired. This would be a hardship in case it should be desired to transfer a small amount of power between two large systems of different frequencies.

Although normally the ratio of the frequencies at each end of a synchronous-synchronous set must remain constant, nevertheless there may be fluctuations in frequency or frequency ratio. Fluctuation in frequency on either or both systems causes load variation on the set and if the fluctuations in frequencies are severe enough, the set will pull out of step. Synchronous machines of this class are normally designed for 50 per cent momentary overload before the pull-out point is reached. In special cases, frequency converter sets may be designed for greater momentary overloads reaching values as high as 200 per cent. This means that momentary fluctuations in frequency or frequency ratio may occur and a set still maintain synchronous operation, provided load changes do not load the set above the pull-out point.

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[1] Central Station Engg. Dept., General Electric Co., Schenectady, N. Y.

*Presented at the Northeastern District, No. 1, Meeting of the A. I. E. E., New Haven, Conn., May 9-12, 1928.*

Excitation for the fields of the synchronous machines may be provided by two direct-connected exciters, one mounted on each end of the set, each arranged to excite the field of one synchronous unit. This gives a very flexible and dependable method of excitation. Sometimes the excitation for both main units is obtained from one direct-connected, or one motor-driven exciter. With this arrangement, individual field control is obtained by the use of rheostats in the field circuit of the main units. The use of such rheostats introduces rheostat losses, and furthermore, the use of a common excitation scheme has the disadvantage that any excitation trouble involves the excitation of both units.

FIG. 1—20,000-KW., 300 REV. PER MIN. SYNCHRONOUS-SYNCHRONOUS FREQUENCY CONVERTER

Motor-operated, phase-shifting devices may be furnished on frequency converter sets when the sets are to operate in parallel. Such a device mounted on one of the machines of each set permits control of load division between sets and enables the operator to add, or remove, a set from the line without any sudden jolt to the system. The phase shifting is accomplished by mounting the stator of one of the machines of the set in a cradle in such a manner that the stator may be physically rotated with respect to the stator of the other unit.

Fig. 1 shows a 20,000-kw. 300-rev. per min. synchronous-synchronous frequency converter recently placed in operation at Providence, Rhode Island, to connect the New England Power Co. 60-cycle system with the United Electric Railway 25-cycle system. The 60-cycle machine is rated three-phase 11,000 volts unity power factor and the 25-cycle machine is rated single-phase 11,000 volts unity power factor. The tested over-all efficiency of the set is 96.26 per cent.

### INDUCTION-SYNCHRONOUS TYPE

Sets of the induction-synchronous type consist of an induction motor driving a synchronous generator and are very similar in normal operation to the synchronous-synchronous type of set, except that the frequency ratio varies slightly with load on the set, due to the slip of the induction motor. The induction motor may be either of the squirrel-cage or the wound-rotor type. The load on one of these sets is controlled in the same manner as the load on a synchronous-synchronous type of set, namely, by adjustment on the governors of the prime movers of either or both systems interconnected. When load on the set is changed, the ratio of frequencies on the two systems is necessarily changed at the same time, which is an undesirable factor in some cases. The straight induction motor, of course, lacks in itself the ability to correct power factor, and therefore cannot furnish leading current, or be utilized as a synchronous condenser when the set is not in use as a tie.

Division of load between two sets operating in multiple cannot be accomplished by a stator phase shifting device, because two induction synchronous sets operating in multiple will divide load according to their speed regulation, and not in accordance with difference in phase position. A change in phase position will not change the speed; therefore the load will remain the same.

### ADJUSTABLE-RATIO INDUCTION-SYNCHRONOUS TYPE

By means of frequency-converter sets of this type, flexible frequency ties are formed between the systems connected together. The two main units consist of a synchronous machine direct-connected to a wound-rotor type induction machine. These two units are not required to operate in synchronism, as was the case with the synchronous-synchronous type. By means of auxiliary equipment, the direction and amount of power transferred through the set is controlled while the frequencies, or frequency ratio, of the two systems may vary within the limits for which the apparatus is designed.

The outstanding features of this type of set are as follows:

1. The ratio of the two system frequencies may vary.
2. Direction and amount of load transferred through the set may be controlled at the set itself.
3. The speed of the set may be controlled for synchronizing purposes.
4. The capacity of the set is determined only by the amount of power to be transferred through the set, as it is not necessary to furnish synchronizing power to hold the two systems together.

5. Leading current for power-factor correction may be furnished by the set to either system.

6. System disturbances will not pull the set out of step as easily as a set of the synchronous-synchronous type.

The synchronous unit of the set is of standard construction, such as used in the ordinary synchronous-synchronous frequency-converter set. The induction unit is of standard three-phase construction with phase-wound rotor, the selection of the secondary voltage being suitable for operation with auxiliary equipment to be described later.

Power may be transferred through the set in either direction by speed control of the induction unit which tends to make the machine operate above or below synchronism. Due to the fact that the speed of the set actually follows the speed of the synchronous unit, any tendency to increase the speed of the induction unit causes flow of power from the induction to the synchronous end and any tendency to decrease the speed of the induction unit causes flow of power from the synchronous to the induction end. The control of power flow in this manner is very similar to the control of a prime mover direct connected to a generator, where output is governed by speed control.

Several methods[2] have been developed for operating induction machines above and below synchronism, one of the principal applications being in steel mill work. The schemes so developed are available for controlling induction machines of adjustable-ratio frequency converters.

All of the schemes referred to are based upon the fundamental principle that the speed of an induction motor may be controlled by controlling its secondary voltage. In the ordinary induction motor, the speed is controlled by adjusting the secondary resistance, increased resistance having the effect of increasing the voltage drop in the resistors and opposing the flow of secondary current. The slip of the induction machine must always be such as to generate voltage sufficient to force through the impedance of the secondary circuit, the amount of current necessary to develop the required torque. If external resistors are used in the rotor circuit to control the speed, the secondary voltage across the resistors is always at slip frequency.

The resistance method of controlling speed of induction motors is not entirely suitable for use in controlling the induction machine of an adjustable-ratio frequency converter, because by this method, only speed control below synchronism is obtained for motor operation and only above synchronism for generator operation. Furthermore, this method permits undesirable rheostat losses. In order to have speed control of the induction machine above, below, and at synchronous speeds for a definite direction of power flow, some scheme such as used for control of steel mill motors is necessary.

In these schemes, the resistor is replaced by a regulating machine, which inserts a voltage of slip frequency in the rotor circuit of the induction unit. When this regulating machine operates as a motor, power is taken from the induction motor rotor, just as would be the case if a resistor were used, but with less loss. When the regulating machine operates as a generator, it corresponds to a negative resistance placed in the induction motor rotor circuit, furnishing power to the induction motor rotor, and giving speed control above synchronism.

In order to present a better idea of just how one of these regulating machines may be applied to an adjustable ratio frequency converter, some of the details of the Scherbius type sets will be mentioned.

FIG. 2—6000-KW. ADJUSTABLE-RATIO INDUCTION-SYNCHRONOUS FREQUENCY CONVERTER

Regulating set is shown in foreground—Installation is in Rochester substation

Seven adjustable ratio frequency converters of the Scherbius-controlled type are now in operation. Five of these sets are rated 6000 kw., and two are rated 5000 kw.

Two of the 6000-kw. sets were installed in 1924, at Rochester, N. Y., where they connect the Niagara, Lockport & Ontario Power 25-cycle system with the Rochester Gas & Electric Company 60-cycle system, (see Fig. 2). Two additional 6000-kw. sets were installed in 1925 at Altmar, N. Y., where they connect the 25-cycle system of the Niagara, Lockport & Ontario Power Company with the 60-cycle systems of the Northern New York Utilities and Mohawk-Hudson. The other 6000-kw. set was installed at Falconer, N. Y., to form a connection between the Niagara, Lockport, & Ontario Power Company 25-cycle system and the 60-cycle systems of Western Pennsylvania. The two 5000-kw. Scherbius-controlled sets were recently installed at Devon, Conn., where they form a connection between the Connecticut Light & Power Company's 60-cycle system, and the New York, New Haven & Hartford Railway Company's 25-cycle system.

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[2] *Theory of Speed and Power Factor Control of Large Induction Motors by Neutralized Polyphase A-C. Commutator Machines*, by J. I. Hull, A. I. E. E. TRANS., 1920, Vol. 39, p. 1135.

"Three-phase Speed Regulating Sets with Separate Excitation," *E. T. Z.*, 47, p. 989, Aug. 26, 1926.

A wiring diagram of the Rochester 6000-kw. Scherbius-controlled, adjustable-ratio frequency converter set, is shown in Fig. 3. The equipment includes a main set, a regulating set, and auxiliary equipment. The main set consists of a 10-pole 7500-kv-a. three-phase 60-cycle 720-rev. per min. 11,000-volt, 80 per cent power factor synchronous unit, a 4-pole 8500-hp., three-phase 25-cycle 11,000-volt, unity power factor induction machine, a 50-kw. 125-volt d-c. exciter, and a 7.5 kv-a. 25-volt a-c. exciter. The regulating set consists of a 475-hp. three-phase 25-cycle squirrel-cage induction motor, direct connected to a 300-kv-a. regulating machine which is a three-phase commutator type unit.

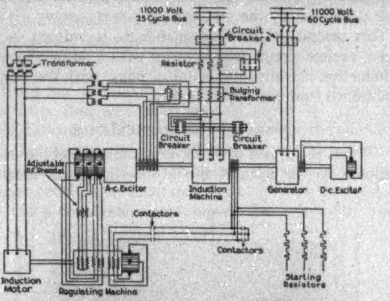

Fig. 3—Diagram of Connections for a 6000-Kw. Adjustable-Ratio Induction-Synchronous Frequency Converter

## Regulating Machine

The requirement of the regulating machine is to supply a voltage to the collector rings of the main induction unit, this voltage being at slip frequency and having a magnitude and phase angle controllable by the operator.

The construction of the regulating machine rotor is similar to that of a d-c. motor. Three sets of brushes on the commutator furnish the required three-phase voltage which is applied to the main induction motor rotor. As the regulating machine is completely neutralized, the current taken from the brushes on the commutator passes through a neutralizing winding on the stator which has the same effective number of turns as the rotor winding. In this way, the armature reaction is neutralized, the turns of the rotor and stator being opposed and balanced.

Due to the fact that it is sometimes considered difficult to obtain good commutation on a-c. commutator type machines, it is of interest to note that commutation on the regulating machine described is exceptionally good.

The regulating machine has the characteristic that whatever frequency is used in its excitation, voltage of that same frequency will appear at the armature terminals. Therefore for this application, it is necessary to furnish the regulating machine with excitation at slip frequency. Furthermore, means must be furnished for controlling the magnitude and phase angle of the excitation in order that the magnitude and phase angle of the armature voltage may be controlled. This required excitation is obtained from the a-c. exciter mounted on the shaft of the main set, as shown in Fig. 3.

## A-c. Exciter

Fig. 4 shows a close-up view of the a-c. exciter. The rotor of this unit has both collector rings and a commutator, and is similar in construction to the rotor of a rotary converter. Power is taken from the commutator through three sets of brushes spaced 120 electrical degrees apart. Means is provided for shifting the brushes, as will be described later. The stator punchings have neither slots nor windings, but provide a path for the revolving flux set up by the three-phase rotor current. The a-c. exciter is really a frequency-changing exciter, as it receives power at line frequency and converts it to slip frequency.

The energy taken from the commutator of the a-c. exciter is always at slip frequency for the following reasons: The a-c. exciter has the same number of poles as the main induction unit and is connected on the shaft of the main frequency converter. The collector rings on the a-c. exciter are connected to the same source of power as the stator of the main induction machine. The voltage supplied to the slip rings creates a magnetic field, which revolves at synchronous speed with respect to the a-c. exciter rotor. The direction of rotation of this magnetic field is opposite to the mechanical rotation of the exciter. The frequency of the voltage taken from the commutator is, therefore, determined by the speed of rotation of the magnetic field in space, and thus is always at slip frequency.

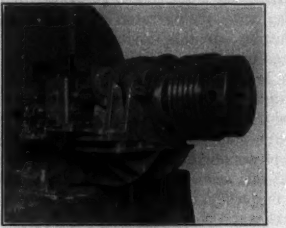

Fig. 4—A-c. Exciter for a 6000-Kw. Adjustable-Ratio Frequency Converter

With the main motor running at exactly synchronous speed, the field of the a-c. exciter is stationary in space and direct current is taken from its commutator. Under this condition, the regulating machine furnishes direct current to the induction unit secondary, as required for the operation of the latter at synchronous speed. With the induction machine running above or below synchronous speed, the magnetic field revolves in space at a speed that is the difference between the speed with respect to the exciter rotor and the mechanical speed; that is, at the speed of slip. Therefore, the voltage on the commutator of the a-c. exciter and on the commutator of the regulating machine is always of the same frequency as the secondary voltage of the main induction unit.

### CONTROL OF REGULATING MACHINE VOLTAGE

Means of controlling the magnitude and phase angle of the voltage taken from the commutator of the regulating machine will next be discussed:

By reference to diagram of connections shown in Fig. 3, it will be noted that the regulating machine has two fields, one, the load field, and the other, the power factor field. Both of these fields are connected to brushes on the a-c. exciter commutator.

The load field of the regulating machine is connected to two sets of brushes on the a-c. exciter commutator, as shown in Fig. 3. By shifting these two sets of brushes in opposite directions, the brushes are permitted to span a greater or less number of commutator bars, thereby furnishing the means of obtaining variable voltage for exciting the load field of the regulating machine. This brush-shifting mechanism is motor-operated, so the brushes may be shifted either automatically, or by the operator. The movement of the brush-shifting on this exciter not only shifts the brushes to include more or less commutator bars but the two brush yokes are shifted in such a manner that the axis of the brushes is shifted.

The shift of axis changes the phase angle of the a-c. exciter commutator voltage. This compensates for the phase angle shift in the regulating machine load field excitation voltage which varies with change in slip frequency. This compensation is necessary in order that the phase angle of the voltage taken from the commutator of the regulating machine will not vary with change of excitation on its load field.

Power factor correction is furnished by the main induction machine supplying a quadrature component of voltage in its secondary circuit. This quadrature component is obtained from the armature of the regulating machine by exciting its power factor field from a third set of brushes located on the commutator of the a-c. exciter. See Fig. 3. This third set of brushes is stationary. The amount of excitation supplied to the power factor field is controlled by adjustment of the rheostat connected in the circuit. The power factor field of the regulating machine is connected Y. Due to the fact that voltage exists at all times across the stationary brushes on the commutator of the a-c. exciter, the power factor may be corrected or adjusted at a time when the main induction machine is operating at its natural slip, that is when zero voltage is impressed across the load field of the regulating machine.

By use of a series or so-called "bulging transformer," as shown in Fig. 3, automatic power-factor correction is obtained to compensate for the change in wattless kilovolt amperes that would ordinarily occur on the induction machine with change in load. The primary of this series transformer is connected in the primary circuit of the main induction machine and the secondary is connected in the a-c. exciter power supply circuit. This secondary winding introduces a voltage in the a-c. exciter circuit which varies with load on the main induction machine and is out of phase with the voltage obtained from the power supply.

### OPERATING CHARACTERISTICS

When the speed of the synchronous machine corresponds to the natural slip of the induction machine at the required torque, no voltage is required from the regulating machine. If the speed corresponds to any other than the natural slip, output is required from the regulating machine, as shown by Fig. 5. This figure shows the output of the regulating machine for different combinations of slip on the induction machine and unity power-factor load on the main induction unit. The ordinates are calibrated in two different ways, the scale at the right indicating the slip of the main induction machine, and the scale at the left indicating the 25-cycle system frequency, under the condition that the 60-cycle system frequency is constant at 60 cycles. Line *C D* shows the natural slip of the induction machine when operating non-regulating, *i. e.*, with zero voltage across the main induction motor collector rings. Limits of load and slip are given by line *A B*, which shows full output of the regulating machine operating as a motor. Line *E F* shows limits of operation when the regulating machine is operating full output as a generator. Lines drawn vertically on the chart indicate operation with constant kw. load transfer through the main set. Points on any such vertical line show how output on the regulating machine

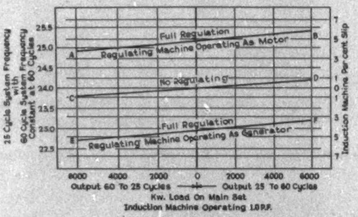

FIG. 5—OPERATING CHARACTERISTICS OF A 6000-KW. ADJUSTABLE-RATIO FREQUENCY CONVERTER

varies with change in slip, while kw. load on the main set is held constant. Lines drawn horizontally indicate operation with constant slip. Points on any such horizontal line show how output on the regulating machine varies with change in load on main set, while the relative frequencies on the two systems are held constant.

When the regulating machine is operating as a motor, the secondary power that would be lost in the resistor method, is transferred through the regulating set back into the line. When the regulating machine is operating as a generator, power is taken from the machine lines and transferred through the regulating set to the rotor of the induction machine.

### LOAD CONTROL

Load on the 6000-kw. adjustable-ratio frequency converter described may be held either by hand, or automatically. When under hand control, the operator changes load on the set by making use of a control switch on the switchboard panel. This control switch is connected to the small motor, which shifts the brushes on the a-c. exciter commutator. For automatic load control, a load relay is provided, which may be set to hold any load desired within the operating range. The load setting is changed by turning a small dial on the face of the relay.

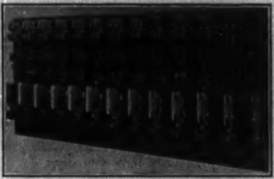

FIG. 6—AUTOMATIC CONTROL PANEL FOR A 6000-KW. ADJUSTABLE-RATIO FREQUENCY CONVERTER

The relay has a wattmeter element and a floating contact, which moves between two stationary contacts. If the frequency ratio changes to increase the load on the set above the relay setting, the relay contacts will close, and automatically shift the brushes on the a-c. exciter and bring the load back to the desired value. If the frequency changes to reduce the load on the set, the relay contacts close in the opposite direction, causing the a-c. exciter brushes to shift to bring the load back to normal again.

### STARTING

Control equipment is furnished which permits automatic starting of the set from the 25-cycle end. The operator starts the sequence of operation by merely pulling a control switch located on the switchboard. Fig. 6 shows the starting panel, with the contactors and relays furnished with one of the Rochester sets. The regulating set and then the main set is automatically brought up to speed. The main induction motor is started with the primary winding connected Y and is later changed over to delta connection. Resistors for starting purposes are automatically connected in the main induction motor secondary circuit, and are later cut out, a step at a time. To reduce the inrush of current to the induction machine and also to reduce the induced secondary voltage at starting, resistors are inserted in the primary circuit, momentarily. After both sets are up to speed, contactors connect the armature of the regulating machine to the rotor of the induction machine. By use of a control switch on the switchboard, the operator can then shift the brushes on the a-c. exciter, to change the speed of the set as required for synchronizing the 60-cycle generator with the 60-cycle system. After the synchronizing has been accomplished, load is transferred through the set in either direction, as desired, by either hand-control or automatic-load-control.

### PROTECTIVE FEATURES

Protective features are provided against a-c. undervoltage, over-speed, over-load, and excessive bearing temperature, and insure that the a-c. exciter commutator brushes are in the neutral position before starting.

The other 6000-kw. frequency-converter sets are very similar to the Rochester 6000-kw. set which has been described in considerable detail. The principal differences in the Altmar and Falconer 6000-kw. sets are their increased frequency range, and the provision for increased power-factor correction in the 25-cycle equipment. In the latter two sets the frequency range was increased 18 per cent, and the power factor of the main induction machine changed from unity to 95 per cent leading. In order to take care of this, the capacity of the regulating equipment was increased, the regulating machine itself being increased in capacity from 300 to 520 kilovolt amperes. With this arrangement, the 25-cycle induction machine can furnish leading current corresponding to approximately 2000 reactive kv-a. to the 25-cycle system over its entire load and frequency range.

The Devon 5000-kw. sets are different in several details from the 6000-kw. sets described. Ordinarily, it would be better to have the induction machine on the low-frequency end of the set, but in this case, a single-phase, 25-cycle machine was required, so it was necessary to place the induction machine on the 60-cycle end of the set. Also, in this case, the regulating machine is connected to the shaft of the main set, which makes an economical arrangement. Furthermore, on this unit provision is made for automatic power-factor control, as well as automatic load control, so the bulging transformers were omitted. Further simplification was made in the Devon sets by omitting the third set of stationary brushes on the commutator of the a-c. exciter, and exciting the power factor field of the regulating machine from one of the sets of movable brushes. Also, in this case, no resistor was furnished in the primary circuit of the main induction machine, because of the lower induced secondary voltage in this unit.

The regulating machines furnished with the 5000-kw. Devon sets have a capacity of 500-kv-a. which is almost as much as the capacity of the regulating machine furnished with the 6000-kw. Altmar sets. However, the Devon regulating equipment is not used for power-factor correction to any great extent but rather to provide an increased range in the frequency regulation.

The regulating equipment is designed to raise the power factor of the induction machine to 90 per cent lagging and to furnish sufficient frequency regulation that the frequency of each system may vary 3 per cent either way, the worse case being when one system is 3 per cent high and the other 3 per cent low.

The main units of the Devon sets have different pole and speed combinations than the main units of the 6000-kw. sets, although the sets in each case connect 60- and 25-cycle systems. With the 6000-kw. sets, the 25-cycle unit has four poles, the 60-cycle unit 10 poles, and the normal speed of the 60-cycle synchronous unit is 720 rev. per min. With the Devon sets, the 25-cycle unit has 6 poles, the 60-cycle unit 14 poles, and the normal speed of the 25-cycle synchronous machine is 500 rev. per min. The Devon set was designed for less speed principally because of the more economical construction of the single-phase, 25-cycle synchronous unit that could be used. This lower speed also permits a saving in the capacity of regulating equipment. The most economical speed for the main set, as far as the regulating equipment is concerned, is 300 rev. per min., because at this speed, the 25- and 60-cycle synchronous speeds coincide, and less regulating is required for frequency variations away from 25 and 60 cycles. However, for the 5000- and 6000-kw. sets, the main units were not designed for 300 rev. per min., because the saving in the cost of the regulating equipment would be more than offset by the increased cost of the main units.

## FIXED RATIO INDUCTION-SYNCHRONOUS TYPE

A paper[3] has been written which covers in much detail the design, theory, and operation of the fixed-ratio induction-synchronous type of set; therefore, only a very brief description will be given at this time.

Fig. 7 shows a diagram of connections for a 35,000-kw. set, which consists of an induction and a synchronous machine.

A portion of the power transfer is made through the shaft of the unit in the ordinary way and the remainder of the power transfer is made electromagnetically through the induction machine by connecting its stator to the 60-cycle system, and its rotor to the 25-cycle system.

The induction machine has 14 poles and therefore a synchronous speed at 60 cycles of 514 rev. per min. However, its rotor speed is held down to 300 rev. per min. by the synchronous unit, this giving 25 cycles slip frequency at the induction machine collector rings. The electrical output of the induction machine rotor is approximately 25/60 of its kw. rating and the mechanical output of its rotor to the shaft of the synchronous unit is approximately 35/60 of its kw. rating.

Full load may be transferred through the set in either direction with unity power factor input. The magnetizing current of the induction machine is supplied through its rotor from the synchronous machine, which is designed to furnish the necessary reactive kv-a. for this purpose.

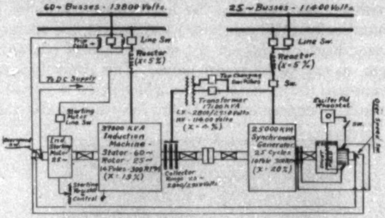
60~ Busses - 13800 Volts.
25~ Busses - 11400 Volts.
Trip Coils
Line Sw.
Line Sw.
Reactor (X=5%)
Reactor (X=5%)
To D.C. Supply
Tap Changing Switches
Sw.
Transformer 17100 KVA
LV - 2800/2950 Volts
HV - 11400 Volts
(X=4%)
Exciter Fld Rheostat
Sw.
Starting Motor Line Sw.
Ind. Starting Motor 25~
37800 KVA Induction Machine - Stator 60~ Rotor 25~ 14 Poles 300 RPM (X=13%)
Collector Rings 25~ 2800/2950 Volts
25000 KVA Synchronous Generator 25 Cycles 10 Pole 300 RPM (X=20%)
Starting Rheostat Control

FIG. 7—DIAGRAM OF CONNECTIONS FOR 35,000-KW. FIXED-RATIO INDUCTION-SYNCHRONOUS FREQUENCY CONVERTER

## APPLICATION

In discussing the application of the different frequency converters described, the synchronous-synchronous type will be used as a standard of comparison because this type is most widely used.

The induction-synchronous type of set has a rather limited field of application, being used principally to furnish power to small loads where the frequency required is different from the frequency of supply. Sets of this type in the smaller sizes are somewhat less expensive than sets of the synchronous-synchronous type but they have the disadvantage of poor efficiency and power factor. Furthermore, the induction machine cannot furnish leading current for power-factor correction, and the variation of frequency with change in load may be a handicap.

The fixed-ratio induction-synchronous type of frequency converter also has a limited field of application, its principal use being in large cities where synchronous converters supplied with a-c. power of two different frequencies are to be tied together on the d-c. side. With this type of set the two a-c. systems are tied together through the same magnetic field, therefore the tie functions practically as a cable tie, the only difference being that the impedance drop in the unit is somewhat higher than would ordinarily exist in a cable tie.

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[3] *A 35,000 Kw. Induction Frequency Converter*, by O. E. Shirley, A. I. E. E. TRANS., 1924, Vol. XLIII, p. 1011.

With a synchronous-synchronous set each machine tends to maintain voltage on the system to which it is connected, and a sudden drop of voltage due to a short circuit on one system does not in the first instant affect the voltage on the other system. The same is true in the case of a sudden phase shift in the system voltage due to a sudden load change. In either case, before any shock on one system can affect the other system the shock must be transmitted through the shaft and this requires time.

On the other hand the fixed-ratio type of frequency converter transmits such a shock instantly and causes a change of voltage on one system to affect the voltage on the other. In other words, the fixed ratio frequency converter ties the magnitude and phase of both systems and acts instantly, while the synchronous-synchronous type ties the phase only and requires time.

With the synchronous-synchronous type of set, a large voltage drop on one system may occur without affecting for the moment the other system. With synchronous converters of the two systems paralleled on the d-c. end, this voltage difference would cause large currents through the converters inverting those on the low voltage system. The fixed ratio type, however, would function in much the same manner as a cable tie allowing parallel operation of the synchronous converters under severe conditions.

The synchronous-synchronous type of set has some operating disadvantages as compared with the adjustable ratio type of frequency converter, but in the majority of cases these operating disadvantages are not sufficient to warrant the purchase of a more expensive set using the adjustable frequency ratio principle. Operating experience shows that in the majority of cases interconnected systems may be so operated that systems of different frequencies may be connected together by synchronous-synchronous frequency converters with no great inconvenience. In case of a system disturbance or system trouble, it may be desirable to disconnect the two systems and in such cases reserve generators are usually available to pick up any load that is dropped. The adjustable ratio frequency converters have the advantage that they may ride through system disturbances with less need of disconnecting the two systems. However, in deciding on the type of set to use in a particular case, it is necessary to decide how much the advantages given by the adjustable frequency converter set are worth. In general, it may be said that sets of the synchronous-synchronous type meet the operating requirements sufficiently well and have the advantage of lower cost, higher efficiency, and simplicity.

Although it is the general practise to use frequency converter sets of the synchronous-synchronous type, nevertheless there are particular applications in which the cost of an adjustable ratio frequency converter may be warranted. Frequency converters of this type are well adapted to connect large central station power systems to industrial or railway systems where the industrial load or railway load may cause considerable frequency fluctuations. Another application would cover cases where the extra cost of the adjustable frequency ratio type will be warranted from the standpoint of being able to control the load at the set itself without need of making adjustments on prime mover governors.

### CHART RECORDS

Chart records given in Figs. 8 and 9 show how well frequency converter sets of the adjustable ratio type operate during system disturbances. The changes in voltage and frequency of both systems interconnected and the kilowatt load transferred through the frequency converter sets are given. The charts in question were taken at Rochester in connection with the 6000 kw. adjustable ratio frequency converter sets previously described.

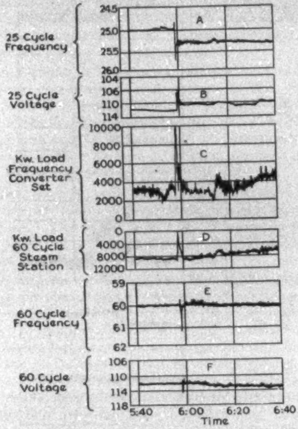

FIG. 8—CHART RECORDS OF A DISTURBANCE CAUSED BY SHORT-CIRCUIT ON 25-CYCLE SYSTEM

System tied to 60-cycle system by two 6000-kw. adjustable-ratio induction-synchronous frequency changers. Chart shows load on one set.

In each case the system disturbance was caused by a short circuit on the 25-cycle system. It will be noted that the short circuits caused a dip in 25-cycle frequency and that the clearing of the short circuits accompanied by load reduction caused an increase in 25-cycle frequency. In Fig. 8 the 25-cycle frequency changed from 25 cycles to approximately 25.3 cycles where it continued to operate. The 60-cycle frequency after a momentary swing, continued to operate at approximately 60 cycles. This change in frequency ratio clearly shows the advantage of an adjustable ratio frequency converter.

At the time of the disturbance shown in Fig. 8, the 6000-kw. frequency converter sets were transferring power from the 25- to the 60-cycle system, each carrying about 2500 kw. load (the chart shows only the load on one set). The increase in 25-cycle frequency to 25.3-cycles caused a sudden increase in power transferred through the sets as shown by 8-C. The sets were momentarily overloaded, the needle swinging to the end of the scale, showing the power exchanged was at least 10,000 kw. on each set. 8-C shows how the load relay operated and quickly reduced the load on the frequency converters back to normal.

8-D, 8-E, and 8-F show that the trouble originating on the 25-cycle system did not cause much disturbance on the 60-cycle system. The sudden increase in load on the frequency converter sets quickly reduced the load on the 60-cycle steam station as shown by 8-D.

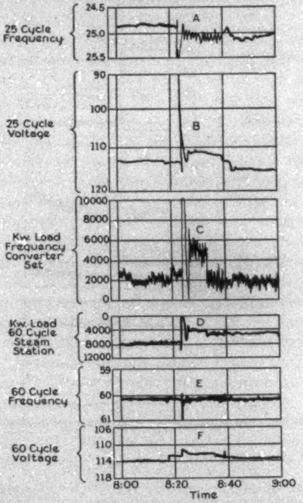

FIG. 9—CHART RECORDS OF A DISTURBANCE CAUSED BY A VERY SEVERE SHORT-CIRCUIT ON 25-CYCLE SYSTEM

System tied to 60-cycle system by two 6000-kw. adjustable-ratio induction-synchronous frequency changers. Chart shows load on one set

The disturbance recorded in Fig. 9 was much more severe than the disturbance recorded in Fig. 8. Here the 25-cycle voltage decreased momentarily to a very low value, the chart needle going off scale. In this case the 25-cycle frequency increased momentarily to approximately 25.5 cycles and remained at this high value for approximately 1½ min. As this large increase in 25-cycle frequency was out of the range for which the frequency converter was designed, the load relay and the load regulating device could not, during this period, reduce the overload on the set. This is shown by 9-C, the load through the set being such that the chart needle remained off scale until the 25-cycle frequency was again reduced. 9-D, 9-E, and 9-F show no great disturbance on the 60-cycle system during this period.

The fact that the adjustable ratio frequency converters rode through these disturbances as well as they did, speaks very well for their operation. The overload relays on the frequency converters were set for a little over double load. Therefore the disturbance recorded in Fig. 9 is about as severe a disturbance as the sets can handle without being tripped. It is very probable that a synchronous-synchronous set would have dropped out of step during the disturbances shown. With the synchronous-synchronous type of set a rise in 25-cycle frequency necessarily causes an equivalent rise in the 60-cycle frequency. Furthermore, during such system disturbances as shown, a synchronous-synchronous type of frequency converter would transfer more power through the set than a frequency converter of the adjustable ratio type.

## GOVERNOR CHARACTERISTICS

The amount of load that is passed through a frequency converter when load is dropped on one of the systems to which it is connected depends to a large extent upon the governor characteristics and speed regulation of the prime movers. The speed regulation of steam turbines is much less than the speed regulation of water turbines; therefore, where the interconnected systems are supplied principally from steam stations there will be less interchange of power through frequency converters during disturbances than would be the case if the systems were supplied with power from hydro stations.

The author wishes to express his appreciation for the cooperation given by E. K. Huntington of the Rochester Gas & Electric Co. regarding the chart records described, and acknowledge the general assistance given by Messrs. J. I. Hull, P. W. Robinson, and O. E. Shirley.

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# Discussion

## INTERCONNECTION OF POWER AND RAILWAY TRACTION SYSTEM BY MEANS OF FREQUENCY CHANGERS

(ENCKE)

## APPLICATION OF LARGE FREQUENCY CHANGERS TO POWER SYSTEMS

(BURNHAM)

NEW HAVEN, CONN., MAY 10, 1928

**P. W. Robinson:** Referring to Table IIB the guaranteed full-load efficiency of 86.9 per cent given for the Devon set proved to be a very conservative figure. Tests of the apparatus as built showed overall efficiency at full load ranging from 90.08 to 89.22 per cent at operating conditions varying from no speed regulation to maximum regulation. A comparison of specified and test efficiencies is as follows:

| Load | ½ | 1 | 1½ |
|---|---|---|---|
| Specified | 80.3 | 86.9 | 88.0 |
| Test | 83.0 | 89.2 | 90.6 |

Referring to Fig. 1, Mr. Encke has for simplicity disregarded the effect of reactance and primary resistance of the induction motor. It may be of interest to mention an important effect of the reactance when power-factor improvement is required, namely that of increasing the amount of flux and consequently the magnitude of the induced secondary voltage. For example, if the natural full-load power factor of the induction motor is 85 per cent with 25 per cent reactive drop and the regulating machine improves the power factor to unity, approximately 14 per cent more voltage is required from the regulating machine assuming that the same speed regulation is maintained. This is the major factor in determining the increased size of regulating machine required for power-factor correction.

There is also an increase in the secondary current required for anything more than a few points power-factor improvement but this is usually of practically negligible amount unless leading power factor is required. When improvement on the leading side is effected the size of the induction motor is likely to be increased as well as that of the regulating machine because not only are the core loss and secondary copper loss increased but also the primary copper loss, instead of decreasing as it does up to unity power factor, increases again.

Another rather interesting effect of the reactance is that, as load is applied to the induction motor, it retards the phase of the voltage required from the regulating machine. This phase shift calls for a change in the phase of the exciting current of the regulating machine as the load is varied. This change is effected in the Devon set by use of the automatic power-factor rheostat as explained by Mr. Encke and in some previous sets by use of bulging transformer.

Mr. Encke has mentioned that the interpole winding of the Scherbius machine at Devon is connected only for below synchronous operation. In explanation of this fact it may be noted that the required amount of speed regulation below synchronism is considerably greater than that above due to the fact that the synchronous speeds of the two main units are different while the specified frequency variations above and below normal are equal. This interpole winding produces interpole flux to set up a rotating voltage in the commutated coils in opposition to the voltage induced in them by the alternating field flux. It was considered advisable in this case to supply such interpole excitation for the higher flux frequency below synchronism but it is not needed above and would complicate the switching to provide it as the connections must be reversed. The ordinary interpole excitation for current reversal like that used in d-c. machines is supplied by extra bars in the compensating winding. By these two means it is theoretically possible in this type of machine to balance all voltages tending to produce sparking at the brushes. As may be observed the practical results attained in this case are almost complete absence of sparking under working conditions.

Referring to the adjustable-ratio induction-synchronous type of converter, the ordinary systems of exciting the regulating machine do not provide a means of building up and stabilizing the voltage on the induction unit to supply power to a "dead" system. Special schemes for excitation may be provided if required to accomplish such results. Unless reduced output is required for such conditions the scheme used should preferably provide for supplying low-frequency excitation rather than direct current to the rotor of the induction unit so that evenly distributed heating will be secured.

**H. F. Brown:** The question has been asked, why tie in a 25-cycle system with another 25-cycle system through a flexible variable-ratio frequency-changer set? There are five important reasons why this was done in the case of Station A.

The value of power interconnections is too obvious to comment on further. In order to connect together two systems of quite different sizes, it is of course necessary with the synchronous-synchronous set to observe certain proportions in the rated size of the set. The variable-ratio frequency-changer set can be any size within the limits of the smaller system. That of course is the first reason.

The second reason is because a railroad load naturally has a ragged peak characteristic. By means of this type set the swings are entirely eliminated from the smaller station.

Further, a single-phase railroad load such as the New Haven Railroad has produces an unbalance in the three-phase system as between phases at heavy loads. Taking it through this type of a set eliminates that tendency.

The single-phase railroad load such as the New Haven, is also lower in power factor than a system such as Station A supplying converters. The power factor of the smaller system is not affected and may be, in fact, improved on both systems by the use of such a set.

The fifth and last reason is the fact of the ability to ride through system disturbances. When it is considered that any railroad system of the size of the New Haven, may be subject to a large number of short circuits or line disturbances in a month, it will be realized that this is an important consideration. It is no reflection on the railroad system to have these disturbances, and the ability to continue operation and ride through them is one of the most important matters that engineers at present have been giving their attention to. The fact that we are able to carry a heavy railroad load through disturbances of this kind shows how this feature has been entirely put in the background as far as electric railroad operation is concerned.

**O. E. Shirley:** The papers have brought out the fact that there are three types of frequency converters available to interconnect two systems. It is sometimes possible by a very preliminary survey to determine the most suitable type, while in some cases it may be necessary to consider difference in initial cost, efficiency, and operating characteristics in considerable detail.

The selection of the variable-ratio type for the New Haven Railway converters, which have been described in these papers, could be made with practically no consideration of the other types.

The comparison of the variable-ratio converter with the other two types in ability to continue operation after severe disturbances may be explained by an analogy of springs. The fixed-ratio type may be considered as a short stiff spring, which will offer a rapidly increasing resistance to variations in frequency of either system, and will break before allowing much displacement. The machine of the fixed-ratio frequency converter with the lower synchronizing torque will fall out of step when its maximum capacity is reached, and it will then be necessary to resynchronize.

The variable-ratio set on the other hand may be compared to a longer spring which will yield much more for the same force. Disturbances tending to cause variations of frequency on one system, will, therefore, not cause an excessive load transfer through the variable-ratio frequency converter, and the load control will very quickly bring the load back to normal after the trouble is over.

These papers have also brought out two different types of regulating machines, one direct-connected or geared to the main units, and the other driven by an induction or synchronous machine which may operate either as motor or generator. There is no general rule for the choice between these types and the one to be used for any particular case must be determined for the size and speed for that case.

**A. G. Oehler:** I should like to know if this type of variable-ratio frequency converter has the same ability to cushion shock occurring on either end of the load, that is, when the shock is transferred in either direction?

**L. W. Encke:** Mr. P. W. Robinson mentions that factory tests made on the Devon sets showed overall efficiencies higher than those mentioned in the paper. The efficiencies of both types of sets given in the paper are values set forth in the specifications. After the installation of the machines, efficiency tests, made by metering the input and the output of the whole set, gave for the Devon sets about the same results as those found on the test floor, and for the Station A machines efficiency figures equal to those on the Devon sets.

Answering Mr. A. G. Oehler's question, it can be said that this type of variable-ratio frequency changer cushions shock occurring on either system. Furthermore, immediately after the disturbance is over, the lead-regulating equipment restores normal load conditions on the set.

**E. J. Burnham:** In Mr. Robinson's discussion he mentioned the need of building up and stabilizing the voltage on the induction unit of variable ratio sets.

In supplying sets of this type we have always stated that sufficient generating power should at all times be connected to the induction unit to stabilize the frequency on the induction end of the set.

By referring to the diagram of connections it will be noted that excitation to the regulating machine comes through the a-c. exciter from the main line. Generating power should therefore be connected to the main line to furnish the required excitation. This generating power is needed to build up and stabilize the voltage on the induction unit when the set is started and it is also needed to stabilize the voltage and frequency during operation of the set.

At the Rochester Station, all the generating power was dropped from the 25-cycle induction end of the set momentarily to see if the set would hold its 25-cycle frequency, and it was found that the frequency did hold somewhat stable for a very brief time. I feel that it would not necessarily continue at this point of stability if dropping of load or fluctuations would take place on the system.

The variable-ratio type of sets now in operation have not been required to furnish power to a dead load from the induction unit; therefore special means of excitation to build up and stabilize the voltage on the induction unit have not been needed.

In case it should be required that the induction machine furnish power to a "dead" system, then special means of building up and stabilizing the voltage would be required. This could easily be furnished by use of a small motor-generator set which would furnish a-c. power at the desired frequency and voltage to the collector rings of the a-c. exciter.

Replying to Mr. Oehler's question, I might state that the variable-ratio type of frequency converter forms a flexible tie between the two systems so that shocks are cushioned as they pass through the set no matter which system receives the original shock.

# The Chicago Terminal Electrification
## of the Illinois Central Railroad

BY R. F. SCHUCHARDT[1] and W. M. VANDERSLUIS[2]
Fellow, A. I. E. E. Associate, A. I. E. E.

### INTRODUCTION

THE development of transportation, using the term in its generic sense, is a measure of the progress of civilization. This includes transportation of material things, as done by vehicles, ships, railroads, and air-ships; transportation of energy from hydro and steam generating stations to the user; transportation of thought by telephone, telegraph, and radio; and now, the transportation of views by television. Transportation reduces time and distance and increases man's range of activities. Communities thrive to the extent to which their transportation facilities are developed.

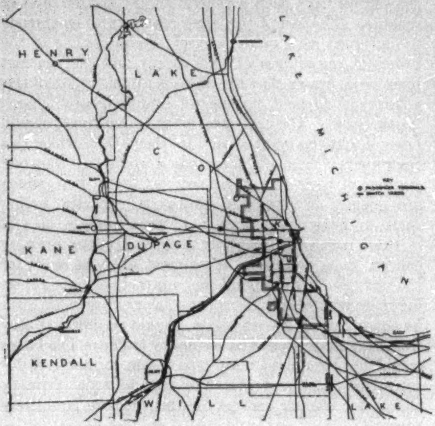

FIG. 1—RAILROADS IN CHICAGO REGION

Chicago enjoys the distinction of having the most extensive railroad facilities in the world. Its local street and elevated car systems are in the front ranks, as is also its electric power development; and its communication system is on a par with the best. This is not said in a spirit of boasting, but to give point to the statement that the methods used to solve the physical problems of that city are of interest to all progressive individuals, and particularly to engineers, since engineering is so much the basis of present-day progress.

In this is found our justification for accepting the invitation to present at this eastern Regional Meeting, a description and discussion of the first electrification of steam railroads to be put into service in the midwestern metropolis.

Let us first try to get a rough picture of the general local railroad situation. Downtown Chicago is served by 21 roads, though only 8 of these reach the central zone over their own track. (Fig. 1.) In the metropolitan area of 1750 sq. mi., there is a population of four million. There are 7726 mi. of railroad trackage and 4330 industries on railroad sidings. Six and one-quarter per cent of all freight in the United States (or 11,400 cars daily) are unloaded here and 4½ per cent are loaded. Nearly 35,000 freight cars are operated daily with a car mileage of over 1,150,000. An average of ten and one-half cars arrive, and the same number depart each minute.

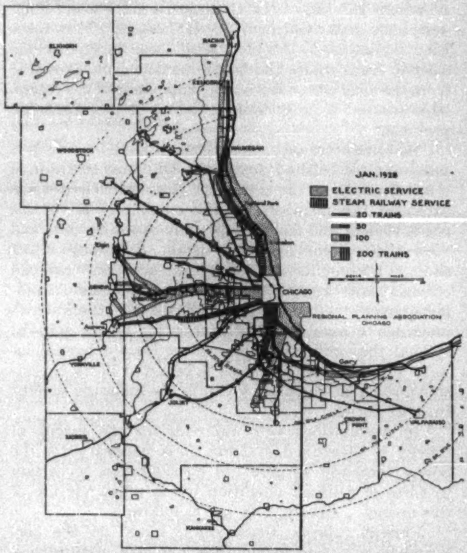

FIG 2—NUMBER OF RAILWAY COMMUTING TRAINS DAILY IN CHICAGO REGION—BOTH DIRECTIONS

In the passenger service, there are over 500 through trains carrying 45,000 passengers and about 1100 suburban trains, carrying 300,000 passengers, arriving and departing from the terminal stations daily. (Fig. 2.)

These figures[3] will help you to visualize the great system of transportation centering in the Chicago region.

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[1] Elec. Engr., Commonwealth Edison Co.

[2] Elec. Engr., Illinois Central R. R., Chicago.

*Presented at the Northeastern District Meeting of the A. I. E. E., New Haven, Conn., May 9-12, 1928.*

[3] Freight data based on 1927 Report of the Committee on Coordination of Chicago Terminals, representing 28 roads. Passenger data estimated from 1923 survey data by same Committee.

With the continued growth of the city and the further expansion of railroad facilities, it seemed inevitable that some day many of the roads would be led to consider electrification of their terminal areas because of congestion, or for other compelling reasons. In anticipation of this time, and with a thorough appreciation of the economy to the community in having the necessary power supply taken from the existing central station system, in 1921 Mr. Samuel Insull, president of the Commonwealth Edison Company, appointed a committee to study the problem. It was Mr. Insull's desire that his engineers be well posted on railroad points of view and railroad operating requirements, so that in subsequent negotiations, the power men could better understand railroad language and railroad needs.

The Committee for the Study of Railroad Electrification, as it was called, was headed by Mr. Britton I. Budd, president of the Public Service Company of Northern Illinois, of the Chicago Rapid Transit Company, and of the Chicago, North Shore, and Milwaukee Electric Railroad. Its membership was drawn from the electric roads under the Insull management, as well as from the local electricity supply companies of the region. This insured a fuller understanding of transportation problems.

The committee met regularly each week for nearly a year, and also visited practically all of the steam road electrifications in the country. Greatest courtesy was extended the members by the officials of all of the roads visited, and facilities to study operating data and view the system in great detail, (including repair shops) were offered freely. In addition, railroad officials and representatives of equipment manufacturers were invited, and came to the committee's meetings to give valuable information on the subject.

That the committee obtained at least a partial insight into railroad problems is reflected in its conclusions, some of which are given in the following excerpt from its notes:

"In negotiations with railroads for the supply of energy to electrified systems, it is necessary for the power company to give full consideration to certain features of railroad operation which affect the use of this energy. Briefly, they are as follows:

"Present railroad operation is based on the performance of steam locomotives and will, naturally,—at least for the present,—be adhered to when a road is electrified. A steam locomotive is a self-contained unit and is not affected by the disability of other locomotives except as the track may be obstructed thereby. The total power available to the railroad at any time is therefore the sum total of all the locomotives in good condition. Train movements are thus limited only by the number of locomotives available and the track capacity. Electric service must approximate this condition as closely as possible. Energy to move trains as per schedule must at all times be available and interruptions very carefully guarded against. In emergencies, excessive amounts of energy may be required and the limit of the free capacity in station, lines, and substations should be available to the railroad.

"The contract should recognize the above requirements and should also express in its rates, terms, and conditions, the superiority of central station service from the railroad's point of view. The contract should reflect the fact that the cost of energy from a general power supply system is less than that from a properly designed separate station of the railroad, and that the service from such a general supply system is more reliable. The fact of the larger reservoir for emergency use afforded by a general supply system is one of the principal advantages of such supply and the contract must be so drawn that the railroad can make use of this advantage without paying an unduly heavy charge for such use. The railroads, on the other hand, should have it clearly pointed out to them that while this reservoir is very much larger than it would be if they had stations of their own, there are still limitations which are usually in line and substation capacity rather than in generating station. Excess reserve in any of these items will naturally require a larger primary charge, since additional investment must be made for the purpose. In drawing the contract, clauses covering emergency energy,—real operating emergencies, such as those caused by accidents, should be differentiated from those due to unusually heavy traffic. The latter would have required additional steam locomotives for the steam road, and therefore an additional primary charge for electric service for this purpose is entirely proper."

At the time of the committee's studies, the Illinois Central Railroad was solving its terminal electrification problem. These studies naturally were in the nature of preparedness steps, looking toward readiness to offer intelligently power service for such electrification, should an invitation for such offer be forthcoming, as it was later.

All members of the committee studiously avoided divulging their separate or collective thoughts with reference to a choice of system for this electrification. The power company stood squarely on the policy of readiness to serve the railroad with power in any form it desired. The contract conditions for the service would necessarily be affected by the choice, but not the willingness to serve. When the railroad made its decision for 1500 volts, direct current, and invited proposals for power supply on the basis of high-voltage energy, (the railroad to do its own converting), or on any other basis if desired by the power company, the latter submitted with its proposal for high-voltage energy, an alternate based on delivery of energy ready for traction use. It was felt that the road would be served better if all essential parts of the power supply were looked after by men especially trained for that work. This is also in harmony with the general interests of the community because of the better economy of joint use of part of the facilities for this and possible other electrifications and for light and general power service.

### THE ILLINOIS CENTRAL PROBLEM

The location of the Illinois Central tracks along the lake shore is not due to the railroad's wishes. It had no choice in the matter. When the city had grown large enough and wealthy enough to want the lake front for parks and boulevards, the railroad was in the way of these improvements, and it was necessary for some kind of an agreement to be reached between the city and the railroad company, involving the surrender of the company's riparian rights and an adjustment of other property in such a way that both the city and the railroad would benefit. For some years there was considerable agitation, also, in favor of the electrification of Illinois Central trains in order to eliminate the smoke which it was claimed detracted from the beauties of the lake front. An agreement was eventually reached between the city and the railroad by which all the desires of the city with regard to the improvements, particularly electrification, would be realized by stages, and by which the railroad, in turn, would receive certain benefits such as the acquisition of certain property rights and relief from the expense of protecting the lake front against erosion. This agreement is embodied in the so-called "Lake Front Ordinance."

On account of the diversity of ownership and of administrative powers of the various interests involved, it was necessary to make the agreement include the South Park Commissioners and also the Michigan Central Railroad. In addition, permission of the Secretary of War had to be obtained for certain of the lake front changes.

Under the ordinance, the railroad was obligated to electrify its complete suburban service by February 21, 1927. The electrification of the freight service north of Roosevelt Road must be completed by 1930, and south of Roosevelt Road by 1935. The electrification of the through passenger service must be accomplished by 1940, provided agreement is reached between the Illinois Central and its tenant railroads with respect to electrification.

The Illinois Central placed its suburban service in complete electric operation in July 1926, a full six months before the limit specified by the Lake Front Ordinance. In addition to the electrification, the railroad made many improvements, a large number of which were not required by the ordinance. These included extensive track changes, grade separations, yard construction, and other works.

The suburban service to be electrified was the most important means of rapid transportation serving the densely populated Hyde Park, Woodlawn, and South Shore districts, as well as the more outlying districts and suburbs directly south of the city. Because of its fast and frequent trains, it was considered the best transportation in the city, notwithstanding the fact that its coaches were old, small, and of wooden construction, and its locomotives equally small and old. The suburban system comprises 37.8 route miles, including 30 mi. on the main line and 8.8 mi. on two branches. There were three classes of trains; namely, local, express, and special. As many as six parallel tracks were necessary in the heavy traffic districts. In the year 1922, when definite plans for the electrification were begun, 21,500,000 revenue passengers were carried by these steam trains.

### SPECIAL COMMISSION APPOINTED TO STUDY THE PROBLEM

In order that this electrification might be along the most progressive lines, the railroad employed three noted electric railway engineers as an Electrification Commission to make an extensive detailed study of the requirements and a selection of the best system to fit these requirements. This Commission was aided by a staff of engineers employed by the railroad company for this purpose. In reaching its conclusion, the Electrification Commission made designs and estimates of the complete costs of electrification of the terminal by each of four different systems. Two years were consumed in this study, and in the autumn of 1921, the report was submitted recommending the 1500-volt d-c. system as the one best suited to this terminal electrification.

With the selection of this system, the Commission's work was ended. The railroad then gathered a force of engineers to design and construct the electrification. In the course of the design, numerous decisions had to be made, involving extensive studies and investigations.

### STUDIES OF THE POWER SUPPLY

Among the major studies that occupied the railroad's engineers was naturally that of the most satisfactory power supply, all things considered. Extensive and careful estimates were made to determine what the power costs would be if the railroad owned and operated its entire power system. These estimates were then compared with the proposals of the power company. In the decision, of course, these cost figures were fully considered, but the operating advantages of obtaining energy from a large centralized power system, and of having the power company perform the operations to provide the energy in the form needed for transportation service also carried weight. As a result of these studies, which were carried on over many months, the railroad concluded to purchase all of its electric energy from the power company.

### FUNDAMENTALS OF THE POWER CONTRACT

The contract which was entered into in 1924, and under which operations commenced in May 1926, calls for the delivery of energy from the substations of the power company. This is at 1500 volts, direct current, on the feeders of the railroad company for traction and 2300 volts, alternating current, for signaling. Three-phase energy at 4000 volts is also provided for the railroad's light and power requirements in its stations and shops. The present supply is taken from seven substations, five of which are within the city and two beyond the city limits (Fig. 3). From the two outside substations the power company supplies the energy by arrangement with the Public Service Company of Northern Illinois, which owns and operates these substations. This latter company, however, does not appear in the contract with the railroad company. The conversion equipment consists of synchronous converters and mercury arc rectifiers, which are described more fully below.

The charges for electricity follow the proved Hopkinson method with a "primary" in recognition of the power company's investment and a step rate "secondary" to cover the operating and service costs. In order that variations in coal cost may be taken into account, there is provision for a change in the secondary charges if the cost and heat content of the coal used falls outside of certain limits.

The primary charge is based on the maximum amount of electricity drawn under normal operating conditions. In order that the railroad company may have the advantage of the power company's large reservoir of power and without the payment of the regular primary charge for additions required in emergencies only, abnormal demands due to such emergencies are excluded in determining the maximum demand for billing. The recognized emergencies are:

1. Abnormally heavy traffic resulting from failure of other transportation lines, unless continuing for more than 10 consecutive days;
2. Traffic arising from extraordinary assemblages, such as fairs, race meets, ball games, conventions, and the like, unless continuing for more than 10 consecutive days;
3. Congestion of traffic arising from a railroad accident, derangement of power supply, or other emergency conditions;
4. Other excessive traffic beyond that usually carried and caused by some unusual circumstance or condition;
5. Hours during which the temperature is + 5 deg. fahr. or lower. (The suburban cars are all electrically heated.)

The limit to the amount of electricity which may be drawn under these emergencies is the capacity of the power company's equipment which may be usable for the railroad company's service during such emergencies. This is one of the features of the contract which makes the central station service of so much greater advantage to the railroad than would be that from its own separate plant. To insure a reasonable, continuing return on the investment made by the power company the railroad guarantees that the maximum demand that it will pay for in any month will not be less than 70 per cent of the highest demand established during the last preceding 12 months. A minimum monthly load factor of 30 per cent is also guaranteed.

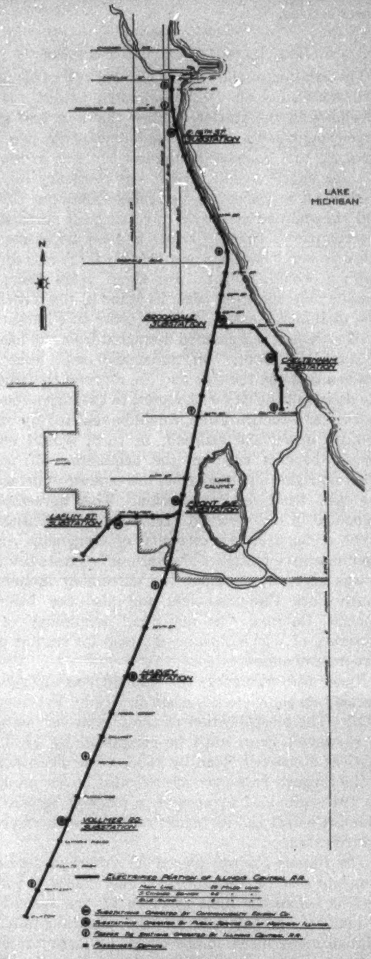
LAKE MICHIGAN
N
BROOKDALE SUBSTATION
CHELTENHAM SUBSTATION
LAKE CALUMET
HARVEY SUBSTATION
VOLLMER RD. SUBSTATION
ELECTRIFIED PORTION OF ILLINOIS CENTRAL R.R.
MAIN LINE
SUBSTATIONS OPERATED BY COMMONWEALTH EDISON CO.
SUBSTATIONS OPERATED BY PUBLIC SERVICE CO. OF NORTHERN ILLINOIS
FEEDER TIE STATIONS OPERATED BY ILLINOIS CENTRAL R.R.
PASSENGER DEPOTS

Fig. 3—Electrification of Illinois Central Railroad (Showing Substation)

One of the railroad's requirements which was finally accepted by the power company but with some misgivings, relates to regulation of the feeder pressure. The high-speed suburban service with short intervals between trains requires a close adherence to running schedule and this, in turn, was felt to demand close voltage regulation. The permitted variation is from 1400 to 1550 volts on the feeders at the point of delivery at the railroad's right of way, which is practically at the substation feeder bus.

Provision is included for additional capacity in new or existing substations, as the increase in load requires. Of course, the power company may install additional equipment in its substations for uses other than this electrified railroad, and also use its equipment to serve other electrifications later if found advantageous to do so.

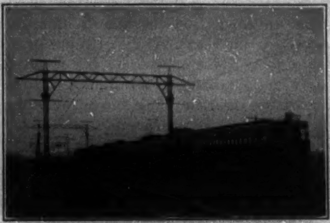

Fig. 4—8-Car Train and Catenary

## Description of Rolling Stock and Distribution System

The suburban cars of the electrified suburban service are of the most modern all-steel type of rapid transit cars, although considerably faster and heavier than the average subway and elevated car. They have been fully described in the technical press[4] at various times, so a detailed description here is unnecessary. All the trains are made up of standard two-car units, each unit consisting of a motor car and a trailer car semi-permanently coupled. In seating capacity and general appearance the trailer car is exactly the same as the motor car. The two-car units can be operated from either end. They reach speeds of 65 miles per hour on level track. They have a very fast acceleration and braking rate, which allows them to make short runs with high-schedule speeds. The express trains and the fast trains serving the outlying districts, however, make long high-speed non-stop runs until they reach the territory they serve.

The trains obtain their energy from the catenary distribution system. (Fig. 4.) The catenary over each electrified track contains four conductors, two of which are contact wires. It is directly connected to the feeder busses of the substations. The conductivity of this arrangement is such that no feeders other than the direct connections between substation bus and this overhead contact system are used. Normally the overhead system is all tied together through the substations and tie station buses (Fig. 5). These stations are so located that in case of faults, the section in which the fault occurs will be automatically isolated. High-speed circuit breakers with good selectivity characteristics are used in all connections. A detailed description of the distribution system can also be found in technical publications.

## The Substations and Their Equipment

The energy supply for the initial electrification is obtained through seven substations located adjacent to, or very near, the railroad right-of-way. Five of these are within the city and are fed from the generating stations at 12,000 volts, 60 cycles over the power company's cable system. The two substations in the suburban region are fed from the 33,000-volt, 60-cycle overhead transmission system of the Public Service Company of Northern Illinois. The line arrangement throughout is such as to provide reasonable reserve so as to insure a high order of reliability.

The major equipment installed in these substations is given in the Table. Figs. 6, 7, and 8 show the exterior of some of the substations.

The 1500 volts direct current for the traction service is derived in part through 3000-kw. synchronous converter units and, in part, through mercury arc rectifiers. Each converter unit consists of two 750-volt elements in series, together with a single-three-to-six-phase transformer. The illustration (Fig. 9) of a converter unit in the Brookdale Substation shows the flash suppressors around the commutator brushes. Another, and principal precaution against possible flashovers at the commutators is in the use of high-speed circuit breakers.

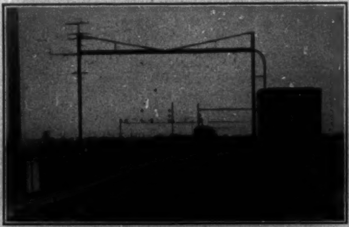

Fig. 5—Feeder Tie Station

The converters are designed to carry 150 per cent rated load for two hours and 300 per cent for one minute with satisfactory commutation. They are of the field-control type where d-c. voltage control is obtained by varying the excitation, thus regulating by means of the reactive current thereby produced.

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[4] Quite fully in *General Electric Review*, April, 1927.

TABLE I
MAJOR SUBSTATION EQUIPMENT

| Substation | Synchronous converters |  | Rectifiers |  | Total kw. capacity | 1500-volt feeders |  | Light and power transformer capacity |
|---|---|---|---|---|---|---|---|---|
|  | No. | Rated kw. capacity | No. | Rated kw. capacity |  | Pos. | Neg. |  |
| E. 16th St. | 3 | 3,000 | 0 |  | 9,000 | 7 | 6 | 1,500 |
| Brookdale | 2 | 3,000 | 1 | 3,000 | 9,000 | 10 | 9 | 1,500 |
| Cheltenham | 2 | 3,000 | 0 |  | 6,000 | 4 | 2 | 150 |
| Front | 2 | 3,000 | 0 |  | 6,000 | 7 | 6 | 300 |
| Laflin | 0 |  | 1 | 1,500 | 1,500 | 2 | 1 | 75 |
| Harvey | 1 | 3,000 | 1 | 2,000 | 6,000 | 4 | 1 | 300 |
| Vollmer Rd. | 1 | 3,000 | 1 | 1,500 | 4,500 | 4 | 1 | 300 |
| Totals | 11 | 33,000 | 4 | 9,000 | 42,000 | 38 | 26 | 4,125 |

The exciter for each converter, mounted on the shaft of one element, is compound wound for constant voltage and the variation in the converter field voltage is automatically obtained by means of a counter e. m. f. regulating equipment. The converters are started from the a-c. side by means of the usual star-delta switches.

Fig. 6—16th Street Substation

A further means of voltage control is provided in the primary winding of the transformer. By means of interlocked oil switches, the connection may be changed under load from the full coil to a 5 per cent tap. Automatic reclosing is provided for the high-speed breaker on the negative lead of the converter with a time delay, which will reclose if the short circuit clears; but if it fails to clear, the positive breaker will also open. This, too, is of the high-speed type.

There are four rectifiers in this service, their location being shown in the table. Two of them, of 3000-kw. capacity, are of foreign manufacture and the other two, rated at 1500-kw. each, are of American make. Both of the 1500-kw. and the 3000-kw. units consist of two bowls each, operating in parallel. A single three-phase transformer with six-phase secondary windings feeds the pair of bowls of the 1500-kw. sets. The 3000-kw. sets are in effect, two 1500-kw. sets operated from one high-voltage switch. Each bowl has its own three-phase transformer. The secondaries are double six-phase connected to the twelve anodes of the bowl. (Figs. 10 and 11.)

These rectifiers are rated to carry 150 per cent load for 20 minutes and 300 per cent load momentarily (American units) or for one minute (foreign units). High-speed circuit breakers (Fig. 12) are provided on the d-c. side of these units. Special reactance coils connected in the neutral of the transformer secondary give the sets an inherent regulation of about 5 per cent. Corrective regulation is accomplished by hand-controlled tap changers on the transformer primary.

All of the 1500-volt feeders have a high-speed circuit breaker on their positive side.

In addition to this equipment for the traction service, each substation contains transformers with regulating and switching equipment for 4000/2300-volt, three-phase light and power circuits for the railroad and for 2300-volt signal service.

To insure safety and reliability, the substations contain a number of interesting features but a detailed description of these would belong to another paper.

## Operating Experience

This electrification has now been in operation for 21 months. From every point of view the equipment has met all expectations, and the complete operation has apparently been successful. The first electric time table was put into effect on August 28, 1926, with a total of 396 revenue trains. Today, 497 trains are being operated on a normal week day. There are 72 additional electric trains run by the Chicago South Shore and South Bend Railroad, which uses the Illinois Central electrified tracks between 116th Street and Randolph Street, making a total of 569 electric trains

Fig. 7—Brookdale Substation

on every week day. The public has shown its appreciation of the electrification by the increased traffic, even though the fares were raised 20 per cent a few months before electrification started.

Fig. 13 shows graphically the increase in revenue passengers from January 1924 to February 1928, and the effect of the electrification is plainly seen. On this graph are also shown the car miles, the seat miles, and the number of daily trains. It may be noted that the car miles did not increase very much after electrification, this being due to the fact that the seating capacity of the new electric car is one-third greater than the average old steam suburban car and the standing capacity is increased still more.

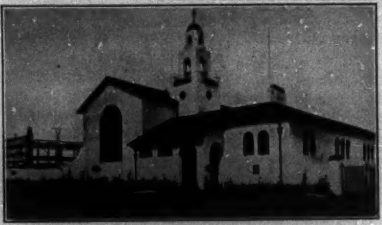

Fig. 8—Vollmer Road Substation

The operation has not been entirely free from troubles but that cannot be expected from an installation of the magnitude of this electrification. However, they have not been of a major character and with one or two exceptions, have not interfered with the transportation service.

Fig. 9—Synchronous Converters (Brookdale)

The operation of this service depends on an adequate and reliable supply of energy. While the Electric Service Agreement between the power company and the railroad company calls for a practically continuous supply of energy, both companies must at all times cooperate very fully in order to maintain efficient service, on account of the electric switching operations involved and because of common maintenance troubles inevitably arising. Such cooperation has been complete in every way, and all routine and emergency arrangements for continuity of service have been handled with efficiency and satisfaction.

Fig. 14 shows the magnitudes and variations of maximum power demand of this suburban service, the load factor, and the kw-hr. per car mile, all measured at the d-c. bus in the substations. The relation of these values to mean monthly temperature can be observed. The fact that the cars are heated entirely by electricity makes the temperature an important influence.

Fig. 10—Mercury Arc Rectifiers (Laflin)

Because of the heavy load fluctuations imposed on the substation converting equipment and of the close regulation specified by the railroad, there was doubt in some quarters that synchronous converters would give satisfactory service and motor generators were suggested. Fortunately these doubts have proved groundless, the performance of the converters having come fully up to requirements.

Fig. 11—Mercury Arc Rectifiers (Brookdale)

The rectifiers also, in general, have performed well,—particularly those of foreign manufacture. In the others, some improvements are still desirable and it is hoped that our American manufacturers will not permit themselves to be outdone for long. Because of the higher efficiency of rectifiers, they are naturally kept on the service for the long hour load. The close regulation is performed by the synchronous converters. As already stated, the exacting regulation specified has been met satisfactorily.

Fig. 12—High-Speed Circuit Breaker (with Asbestos Chute Tilted Back)

That very important link, without which the major equipment would not perform so satisfactorily,—namely, the high-speed circuit breaker,—has done all that was expected of it. Both in correct selectiveness and in effective current interruption its behavior has been excellent. The duty on these devices is at times heavy. They have effectively limited to a negligible degree the damage resulting from accidental short circuits in overhead wires or rolling stock.

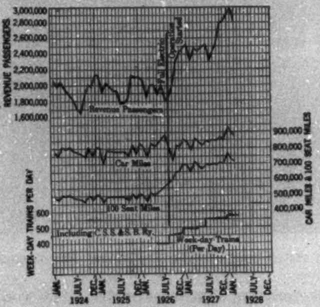

Fig. 13—Traffic Data

## POWER DATA

The maximum demand of the electrified road on the power system has thus far been approximately 24,000 kw. The total 1927 energy use was slightly under 59,000,000 kw-hr. The annual load factor was thus about 28 per cent. The monthly load factor varied from 32½ per cent to over 39 per cent.

At the time of the power companies' maximum load this last winter, the railroad's load was about 7 per cent lower than it was at the time of its maximum, which occurred a week earlier. It should be noted that this diversity existed even though the portion of the road thus far electrified—suburban service, only, in winter has a daily load characteristic which closely approximates that of the power company. With the addition of the freight and of the through passenger service, this diversity should be much higher.

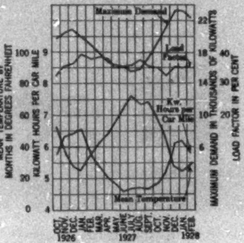

Fig. 14—Power Data

The increased business that the railroad has enjoyed since electric operation was begun has shown the inadequacy of the estimates originally made with reference to probable power requirements when the other branches of its service are added. The revised estimates have not yet been completed.

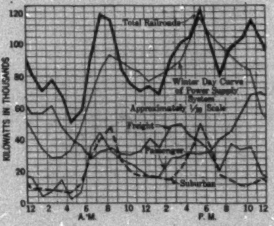

Fig. 15—Estimated Load Curve for 1928 for all Railroads in Chicago Assuming them to be Completely Electrified

The power company has made some rough estimates with reference to the entire Chicago railroad service, which are given in Fig. 15. This shows the shape of the daily load curve for a winter day. Superimposed on these curves is a typical curve of the regional power system load (but to a different scale). The combined railroad load is estimated to have an annual load factor of about 62 per cent. Further improvement may be possible by shifting freight time tables. From the power company's point of view, this is a very desirable load. The railroads, on their part, receiving their supply from the large power pool, would enjoy, among other things, the advantages of the high generating efficiency of the rapidly growing system, the comparatively large reserve, and the absence of heavy capital requirements for power purposes.

The estimated maximum demand for 1928 for all the railroads in the Chicago region, were they electrified, is on the order of 125,000 kw. This is but a little over 8 per cent of the interconnected generating capacity of the region; actually less than the single item of reserve normally carried by the power companies. Two points are brought out by these figures: (a) that the investment necessary to provide the power requirements of electrified railroad business is not a burdensome item in the power company's budget, and (b) that the particular form of energy required by the railroad will not have any appreciable influence on the general engineering plan of the power company.

While these conclusions are based on the conditions existing in the Chicago region, they will probably be found to apply with at least equal force elsewhere. The ever enlarging area being covered by substantial power systems with their far flung transmissions is constantly increasing the ease of obtaining a suitable supply of energy for railroad electrifications, as the railroads find, with the progress of time, that economic or other conditions make electrification desirable. Power systems will serve the railroads most effectively when there is a willingness to serve in the manner demanded so that the railroads in turn can produce their service as best suits the requirements of good transportation.

## Discussion

**E. R. Hill:** One of the very interesting and important features of the Illinois Central Electrification, as described in this paper, is the contract for the supply of power between the Railroad and the Commonwealth Edison Company. Probably the most unusual feature of this contract is the supply by the power company of converted current at the seven substations located along the railroad. It is more usual for the power company to supply alternating current at a single point and for the railroad to transmit and convert or transform this power itself.

The paper calls attention to the practise which has now become quite general, and which is regarded as absolutely essential in connection with railroad electrification work, for the power company to supply excess demands in railroad emergencies without affecting the demand charge. In other words, the demand charge is determined by the road's power requirements under normal conditions, and emergency drafts of power do not affect the demand billing. This is very important and really essential in connection with railroad operation because of the fact that abnormal and emergency conditions occur much more frequently in railroad operation than in probably any other industry, and it is impossible for the road to control or prevent the occurrence of such exceptional demands.

The most recent large power contract for railroad operation that the writer has knowledge of was negotiated and consummated last year between the Pennsylvania Railroad Company and the Philadelphia Electric Company at Philadelphia. This is a continuation and enlargement of an earlier contract covering the supply for the Pennsylvania Railroad's suburban service in Philadelphia, intended to provide for all traction requirements in that territory including through electrification between New York and Washington and elsewhere, if and when carried out, for a period of 20 years.

The power company contracts to supply the power at 25 cycles single-phase 13,200 volts at certain main supply points in the vicinity of Philadelphia or elsewhere as may be arranged from time to time. The railroad steps up the voltage to 132,000 and transmits at this pressure to its various transformer stations along the railroad.

The outstanding new feature of this power agreement is that the charges or rates are based on the actual cost to the power company of producing power in its generating stations, and of transmitting it to and converting it at the supply points. This actual cost, of course, includes fixed charges, general expenses, and all other items properly entering into the total cost.

In order that the railroad may be protected against any unforeseen high cost of producing power, the power company guarantees that the demand charge and the energy charge shall not exceed certain stipulated values that were estimated and set up at the time of the negotiations. Such guarantees are based on specific cost of coal and labor. Maximum rates for fixed charges are also stipulated.

Some of the other main features of the contract are:

Demand determined monthly based on three maximum normal clock hours per month.

Abnormal demands resulting from accidents, derangement of power supply, abnormally heavy traffic, or severe weather conditions, shall be disregarded in determining the maximum demand.

Demand may not be less than 75 per cent of any previous maximum demand.

Guaranteed monthly load factor is 30 per cent.

Guaranteed power factor is 55 per cent.

If lower rates are subsequently made to other consumers under similar conditions of supply, the railroad shall be entitled to the same rates.

At an average monthly load factor of 62 per cent, a coal cost of $5.00 per net ton, present labor rates, and guaranteed maximum demand and energy costs, the average cost to the railroad at the supply point or points under this contract works out 0.75 cent per kw-hr.

**Sidney Withington:** The question of power supply for railroad electrification is one not only of economy, but of reliability. These two important considerations do not necessarily go hand in hand; in fact, it often happens that a balance or compromise between them is necessary. For instance, it may be more economical to develop a single central supply of power for a given electrification project than to provide several sources of feed, but a single supply may mean that power-transmission facilities must be installed along the railroad right-of-way in close proximity to the tracks, with consequent danger of interruption on account of derailments. The right-of-way, furthermore, often passes through thickly settled communities where the clearance is restricted and where danger of trouble from a possible fire on adjacent property is considerable. Any hazard which results in cutting the power line in two obviously is going to be serious if it results in a complete prostration of service beyond the break.

As an alternative to a single point of supply there may be considered a main or central feed to serve as a "back bone," with supply points of relatively less capacity near each end of the electrified zone, so arranged that in the event of a failure of the main supply or a break in the transmission facilities the auxiliary source, may carry at least a portion of the load and thus take care of the most important service until normal conditions are resumed. Such an arrangement obviously costs somewhat more than a complete concentration, but the resulting increase in reliability is often worth the added cost in an important electrification project.

A third possibility which may sometimes be practicable is the tying at various points to a single large power system with a transmission network entirely independent of the right-of-way of the railroad. Such a system is often fed from two or more independent power plants or interconnected with other power systems. In an arrangement of this kind any single interruption of power or transmission would normally not seriously affect railroad operation. If conditions are favorable, such an arrangement is from many points of view quite ideal, for it allows advantage to be taken of the maximum railroad load factor with consequent minimum cost, and at the same time obviously produces maximum reliability. The choice of power supply in any given instance obviously depends upon local conditions and facilities readily available.

Although in many instances a generated frequency of 25 cycles is available commercially which makes possible a tie directly into railroad traction feeders, the power available from a large commercial system, is usually 60-cycle three-phase, and is thus often not adapted for direct supply without modification for heavy electric traction, and therefore, regardless of the system of electrification, some form of conversion apparatus is generally necessary if power is purchased. If a railroad produces its own power the characteristics of the power supply of course are correlated with those of the system adopted.

The two electrification systems of power distribution most often employed in this country are (2) direct-current, operated at various voltages from 600 to 3000, and (1) alternating-current single-phase usually operated at 25 cycles and 11,000 volts. To adapt three-phase 60-cycle power from a commercial 60-cycle supply to either of these systems requires some form of substation apparatus, which in the case of direct current may be mercury-arc rectifiers, motor generators, or rotary converters, and in the case of single-phase takes the form of motor-generator frequency changers.

Other things being equal, the purchase of power by a railroad for traction purposes should be more satisfactory than the operation by the railroad of its own plant. The capital requirements for railroad electrification are necessarily very high at best. The cost of power distribution facilities required to convey power to the collecting devices of the motive-power units runs into many thousands of dollars for each mile of track electrified. The acquiring of locomotives or cars on an equipment trust allows postponement to some extent of a portion of the immediate capital requirements, but the purchase of power will eliminate the relatively large capital which would be necessary for its own power-plant installation.

It is, however, necessary that power companies which are interested in supplying power for railroad electrification shall consider all the aspects of the questions, such as diversity of load compared with other customers (for much of the railroad load, especially freight, occurs during the night), and the volume of business involved.

With growing efficiency of power-plant apparatus made possible, especially by concentration in large units, it is logical to expect that the production of power by organizations specializing in such production would be more economical than production by railroads themselves, provided, however, that such economies are not obtained at the expense of too high investment charges, so that the consumer does not have the benefit. It should be borne in mind in this connection, also, that railroads are often in a position to purchase coal more advantageously than power companies.

Railroads do not as a rule pay as high a rate of interest on capital investment as do power companies, and this should be taken into account in determining the demand or primary charge which represents the cost of the money invested in plant and associated facilities. If a railroad installs its own plant, it may justly contemplate calling upon its reserve capacity for such emergencies as may sometimes occur in the course of its operation; and a power company in taking on a railroad power supply should be prepared to carry the load, during abnormal conditions over which the railroad often has no control, without subjecting the railroad to penalty in establishing demands. As has been pointed out by Messrs. Schuchardt and Hill, most of the important agreements for power for railroad traction purposes now recognize this important point, to the mutual advantage of all concerned.

The early New Haven electrification, inaugurated in 1906, was originally supplied from a railroad-owned power plant located at Cos Cob, Conn., which is not far from the center of the system load between New York and New Haven. Commercial power at that time was not available. The Cos Cob Plant, with a capacity of about 13,000 kw., served the initial installation between New York and Stamford. In 1912 the plant was enlarged to about 32,000 kw. capacity to carry the New York, Westchester & Boston and the Harlem River Branch freight traffic and the electrification through to New Haven which was inauguarated in 1914.

In 1915 there was added to the power system a supply from the United Electric Light & Power Company at West Farms, N. Y., the power being generated at the Sherman Creek Power Plant of that company. This connection is supplied from turbo generators used exclusively for railroad service, and although the power company's machines share with Cos Cob the power swings, nevertheless with proper supervision considerable accuracy in the control of load and consequent supply of energy is possible.

With the growing load on the New Haven the question of a power supply at the east end of the electric zone was considered. The alternatives were (1) concentration at Cos Cob with independent high-voltage transmission and step-down substation at the east end of the zone, and (2) entirely independent supply at the east end, somewhat analogous to the West Farms supply. The result was a decision in favor of independent supply and the installation at Devon, Conn., of two 5000-kw. (continuous) frequency-changers for the purchase of power from the Connecticut Light & Power Company, and at New Haven of one machine of similar capacity for interchange in either direction of surplus power with the Connecticut Company.[1] These facilities automatically allow continuous or definite control of load as desired, regardless of relative variations of voltage, load, or frequency in any of the systems involved.

An extension of the New Haven System over the New York Connecting Railroad and on the Long Island Railroad to Bay Ridge, N. Y., made desirable a connection with the Pennsylvania Railroad power system at East New York which could be used in emergency. A motor generator similar to that at New Haven was thus installed at that point. That motor generator, as well as all of the other apparatus of that type, is available as a synchronous condenser to maintain a favorable power factor. There are thus now in service on the New Haven System five points of supply: East New York, West Farms, Cos Cob, Devon, and New Haven.

There is no doubt that the concentration of power at Cos Cob would have been more economical than the policy of decentralization which has been adopted, but the consideration of reliability justifies the extra expense. While Cos Cob is the main source of supply, the auxiliary sources are of sufficient capacity in the event of an emergency to provide the continuance of at least the more important traffic, and it is our opinion that there is a satisfactory balance between the two important considerations, economy and reliability.

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[1] *Interconnection of Power and Railway Traction Systems by Means of Frequency Changers*, by L. Encke, see p. 1056.

**G. I. Wright:** I want to make a few remarks about the economic aspects of such a service as the electrified Illinois Central, and these in general will apply to any suburban or commuter service for passenger traffic for a large city.

The handling of such a business is not particularly attractive from an economic standpoint, but although passenger revenues and passenger business for the railroads as a whole are falling off, yet suburban business is either holding its own or in most cases increasing.

The paper states that the load from the power company's standpoint is a favorable one, and I presume it means economically favorable. Suburban passenger business from a railroad standpoint is in general not economically favorable, and one of the most interesting things in connection with the electrification of such a service is its effect upon the net return. This business is a low-load-factor business; actually the ratio of the average number of passengers hauled to the maximum number hauled during rush hours is around 25 or 30 per cent. This means that the rolling stock and the total investment in railroad facilities necessary to handle the business is largely idle during the greater portion of the day.

A power company in selling electricity gets a return on a low-load-factor business by having a rate which takes into account the maximum demand. I believe the fact that their rates bring them a return for the service rendered and the investment necessary to handle that service is largely responsible for the growth and success of the power companies in this country.

With a railroad handling commuters this is not so. The rate for passengers who ride during the rush hour is very much lower than the rate for a ticket to ride during any part of the day. The latter have to pay 3.6 cents a mile. The rate for the commuter, in the case of the Illinois Central, is as low as 0.6 cent a mile. This means that for this low-load-factor business they are getting a very low unit price.

I do not believe that power people who are accustomed to their unit rates varying with the load factor of the load realize what the railroads are up against from the standpoint of economically getting a return on the service rendered. The railroads have probably not done as much to correct this condition as the power companies have. The power companies have insisted on a rate which takes into account the load factor. They have also given off-peak rates and have constructively gone at the problem of building up their load factor and increasing the off-peak business. The railroads under steam operating conditions have done very little. After electrification it is possible to make improvements in this respect. You can operate economically shorter trains and more frequent train service during the middle of the day and thus make a bid for that business as has been done by the Illinois Central. The cost of fuel for steam operation is the same no matter what time of day it is burned in the locomotive, while the cost to the railroad of electric current used during the non-rush hours is only a fraction of the cost if used during the rush hours, as it does not increase the power company's investment or the demand charge which brings them the return for this investment.

The Illinois Central's electrified service with its faster schedules and greatly increased frequency of train service in the non-rush hours, has not only attracted new residents to the territory served but has increased the riding habit of those already there. The Sunday business has also been greatly increased by this method. The Illinois Central has also put into effect a reduced round-trip rate of a fare and a half and has made a bid for the business of those who would hesitate to pay 3.6 cents a mile to make a trip down town. I believe they could well afford to have made this rate still lower.

It must be highly gratifying to the management that they have been able to turn a large operating loss into an operating profit sufficient to pay some return on the increased investment, and this with lower rates than are charged for most similar services. This fact should also be of interest to the management of other railroads who have not as yet electrified their suburban services.

**H. C. Sutton:** Most electrifications in the East have been for suburban service. A factor that is very interesting to the central stations is that with the extension of the electrifications to take in trunk-line railroads, the load factor of 26 to 30 per cent which is now obtained on suburban service, will be increased to a load factor of over 60 per cent with combined suburban and trunk-line electrification.

A study is being made of the electrification of an important railroad in the East where the peak load occurs in the early morning hours, due to the schedule of getting the trains into the metropolitan terminal early in the morning. This should result in a high diversity factor for the central station for this type of load.

There are some reasons why purchase of central-station power should prove of benefit to the railway, which have not been brought out in the papers. Take, for instance, the cost of supplying service by the central station as compared with the cost of the railway company's putting in its own generating station. If the railway furnishes its own supply it would have to build a plant at considerable expense, namely, a modern plant of the day in which it is designed and built. However, past history would indicate that in a ten-year period that plant would be relatively uneconomical as compared with plants built at later dates. Under central-station supply additions to the generating capacity are continually made to take care of the rapidly growing load, where in many locations the load doubles in five- or six-year periods. Central stations, therefore, are continually building new and better plants with an advance in higher efficiency, with the use of larger turbine units, etc., bringing down the cost of power from year to year. The railway company, therefore, should benefit in future readjustment in rates when based on the cost of supply.

There is another interesting fact in regard to suburban railway electrification and that is the rate of the growth of traffic is greater than prior to the electrification due to the greater ease and comfort in riding on the electric trains.

**O. K. Marti:** I was very much interested in the paper by Messrs. Schuchardt and Vandersluis, especially since mention is made in it of the new converting equipment used, the mercury arc rectifier. This is the first main-line electrification with such devices in this country. Further, because of its peculiar operating conditions, this line imposes very high duties on the converting equipment, and it was therefore very interesting to learn more about the operation of the rectifiers.

As we all know, rectifiers have a very high efficiency at high voltages. The efficiency at 1500 volts is much higher than that of any other converting device. Since rectifiers for 2400 and even 3000 volts are just as satisfactory in operation, it would be interesting to learn whether Mr. Schuchardt could give any information as to the possibility of operating such a railroad as the Illinois Central at these higher voltages.

Another thing which I should like to bring out, and on which I should like to hear some comments, especially from railroad engineers, is whether a higher voltage drop on the trolley wires would not be permissible, and whether this would not be more economical from many points of view. Thus far compounding windings have always been used on old converting equipment, and other means as well have been employed to keep the voltage as constant as possible.

During the discussion of this paper Mr. Wright mentioned that a high load factor allows a smaller unit to be used for converting alternating to direct current, and is therefore very desirable. It seems to me that by allowing a high voltage drop in the machine we would get a still better utilization of the units, especially if the converting devices are distributed along the system instead of being concentrated in one place.

This directly relates to the question of the location and spacing of substations, namely, should rectifiers be grouped in substations of comparatively large capacity or would it be more economical and advisable to locate them along the railroad line, distributed in smaller stations. An extensive railroad system which is at present being electrified is the Berlin Rapid Transit, which consists in part of a belt line uniting all the suburbs of Berlin. In this system the rectifiers are spaced very closely, and are located in the existing structure, in this case in the arches of the elevated structure supporting the tracks of the railroad.

**P. H. Hatch:** Electrification has been so far tied up intimately with power supply. In the future, it seems to me, we should consider the effect of independently propelled locomotives similar to, and having the advantages of, the electric locomotive but without the complications of the distribution system. I refer to the Diesel electric locomotive or the straight Diesel unit. It promises the combined advantages of the electric equipment. In the future what effect will this have on our power requirements?

Another problem is the question of standardization of frequency for railroad power supply. Those of us who are using the 25-cycle single-phase system are wondering if 60 cycles becomes standard what we will do for power conversion. Will we have to supply rotating machinery for converting our power? If such is the case, then some of the advantages of a-c. electrification in this country may not be entirely realized.

**R. F. Schuchardt:** The question Mr. Marti has asked me should have been asked of Mr. Vandersluis since it involves the railroad's choice of electrical system. Mr. Vandersluis will probably, however, agree with me that to go into this question at all would be to open up the entire subject of systems for railroad electrification, which is quite beyond the purpose of this meeting. However, it might be worth while to point out to Mr. Marti that among the deciding factors in the selection of trolley voltage, the efficiency of the substation equipment is not a paramount one.

**W. M. Vandersluis:** Our paper was prepared especially to bring to the attention of the power companies the necessity of studying the power needs of steam railroads contemplating electrification and meeting those needs squarely in offering their services. That the railroad requirements are different has been clearly brought out in the paper and in the discussion.

The agreement in question, covering service to an electrified steam railroad at seven different points and with all the required feeders to the right-of-way line, is the first of its kind. Naturally, it was entered into by the railroad company with some misgivings at times as to how it would work out. The length of the agreement so indicates, although it would have been much simpler if left entirely to the engineers of the two organizations.

It has been in operation for over two years and so far nothing has come up to indicate the necessity of any particular change in its various clauses. This is due not so much to the wording of the agreement as to the spirit of cooperation evidenced, we believe, by both parties in their desire to understand and meet the service requirements of each.

Power companies contemplating similar services to electrified steam railroads can profit by the attitude of the companies in question and the results obtained.

# Effect of Street Railway Mercury Arc Rectifiers
## On Communication Circuits

BY CHARLES J. DALY[1]
Associate, A. I. E. E.

***Synopsis.**—This paper describes the effects experienced on the telephone circuits from the two mercury arc rectifier substations recently installed in Bridgeport, Conn., and shows in table form the relative magnitude of the interfering effects between rotating equipment and mercury arc rectifiers as a means of energizing the street railway system. The method and the type of apparatus used to reduce the effects experienced from the rectifiers are also described.*

* * * * *

THE application of the mercury arc rectifier for supplying power to street railway systems is now attracting a great deal of attention. In considering such an installation the question naturally arises as to its effect on communication circuits. In December 1927 all the current for the operation of the street railway system serving the territory in and around Bridgeport, Conn., was obtained for the first time from two mercury arc rectifier substations. A comparison of the relative interfering effects on the telephone circuits between this method and the previous method used for energizing this railway system was obtained and is described in this paper.

Both substations were not placed in operation at the same time, there being an interval of about four months between the installation of the larger station at Bridgeport and that of the smaller at Stratford. During this interval the larger rectifier station was operating in parallel with the rotating equipment of the old generating station for a short period of time only. Measurements of the interfering effect of the noise experienced on the various types of local telephone circuits were made just prior to the placing in service of the first rectifier station and immediately after each substation was connected on the line, as well as after temporary remedial measures were applied. The measurements obtained under these various conditions of energizing the railway system are shown in the accompanying tables.

### TYPE OF TELEPHONE PLANT

The Bridgeport exchange is a multi-office area served by three sub-offices, two of which are in the same building located in the business center of the city within one-quarter of a mile of the larger rectifier substation. The third sub-office is located in Stratford, approximately four miles from the Bridgeport central office building and within a quarter of a mile of the smaller rectifier substation. The interoffice trunk circuits connecting the Stratford telephone office with the Bridgeport main telephone offices are in underground lead-covered paper-insulated cables and with the exception of about one-half mile are parallel to and in the same streets with the railway system. See Fig. 1.

All subscriber telephone circuits on the same streets with the railway circuits are in lead-covered cables or twisted pair wire. The greater portion of the cable plant is in underground construction, although there are several relatively long runs where the cables are on poles jointly occupied with street railway circuits, and in a few instances on the same poles with both positive and negative railway feeders. There are no open-wire telephone circuits on the same streets with the street railway circuits.

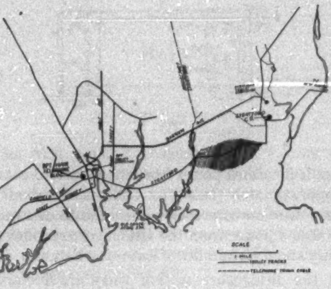

Fig. 1

The types of telephone service provided include standard individual line service on which metallic ringing is used, standard two-party selective and four-party semi-selective service, and private-branch-exchange service. In the selective service both the two-party and the four-party semi-selective types are provided.

It might be well to describe in some detail the signaling circuit used with the selective type of service. Fig. 2 shows the schematic wiring for a two-party selective circuit. It can be seen that each side of the telephone circuit is connected through a condenser, usually of 1 $\mu$ f. capacity, and then a ringer to ground. The ringer has a d-c. resistance of at least 1000 ohms and an impedance at 800 cycles of over 30,000 ohms.

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[1] Transmission and Protection Engineer, Southern New England Telephone Co.

This connection to ground is used only for ringing purposes and not for transmitting the voice frequencies, as may be judged from the impedance in the ringing circuit to ground. With this arrangement the bell at one station can be rung independently of the one on the other side of the circuit.

The four-party semi-selective service is similar to the two-party service described above except that two stations are connected to each side of the circuit. With this arrangement, however, both bells on the same side of the line are rung when the ringing current is imposed on that particular side of the circuit. In the case of the individual-line service, signaling is obtained on an all-metallic basis by bridging the bell circuit across the telephone line.

### STREET RAILWAY SYSTEM

The street railway system consists for the most part of a double-track system with the rails and earth, supplemented along some of the routes with negative feeders, as the return circuit. Fig. 1 shows the railway system within the Bridgeport and Stratford city limits and the relative locations of the two rectifier substations. An interurban line extending to New Haven is furnished power from the Stratford substation for approximately half the distance or about seven miles. Another interurban line runs to Norwalk and is furnished power from the Bridgeport rectifier station for only about eight miles of its entire distance.

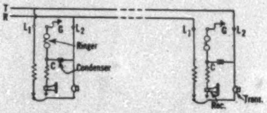

FIG. 2

At the Bridgeport station there are five six-phase rectifiers which are energized from a 13,900-volt, three-phase, 60-cycle power line and deliver 600 volts direct current to the street railway system. Each rectifier is rated for 2000 amperes. Two similar type rectifiers are in the Stratford substation operating under the same conditions and in parallel with the Bridgeport station.

At the time of the writing of this paper a temporary filter had been installed in the street railway circuit in the Stratford rectifier station, but none had been installed at the Bridgeport rectifier station, although permanent filters were in the process of manufacture for both stations.

### METHOD OF MAKING MEASUREMENTS

In order to determine the interfering effect experienced by the telephone subscriber under normal operating conditions, all measurements were made from the receiver terminals of the telephone instrument with the circuit connected through the switchboard to another telephone set located in the central office building. Measurements were obtained for various conditions that would be found in the practical operation of the telephone system. Such a condition, for example, is where two stations, due to the cancellation of the service or to the moving of the subscribers, have to be disconnected from a standard four-party semi-selective circuit leaving two stations connected to the same side of the circuit. This gives the maximum unbalance produced in this type of apparatus under the various operating conditions.

### RESULTS OF MEASUREMENTS

Prior to the cutting into service of the Bridgeport rectifier station, measurements of the noise on telephone circuits under various conditions were made at some 140 locations in Bridgeport and 50 locations in Stratford. After the installation of the rectifiers, measurements were made only at representative locations.

In Table I is shown the magnitude of noise obtained before and after the Bridgeport rectifier was cut into service in parallel with the rotating machinery in the old generating station. These measurements are representative of the general noise situation on the local telephone circuits.

TABLE I

NOISE UNITS

| Location Bridgeport | *R*-(*T* & *R*) | | *R*-(*T*) | | *R*-bridged | | 2-*R* (*T*) | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| A | 20 | 50 | 35 | 75 | 20 | 50 | 35 | 100 |
| B | 10 | 20 | 20 | 35 | 0 | 10 | 20 | 50 |
| C | 20 | 35 | 20 | 50 | 20 | 35 | 35 | 150 |
| D | 35 | 100 | 50 | 125 | 35 | 75 | 75 | 250 |
| E | 20 | 50 | 20 | 75 | 20 | 35 | 35 | 100 |
| F | 20 | 50 | 35 | 75 | 20 | 50 | 50 | 150 |
| Ave. | 20 | 50 | 30 | 70 | 20 | 40 | 40 | 135 |
| Stratford | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| A | 20 | 35 | 75 | 100 | 20 | 35 | 75 | 200 |
| B | 20 | 35 | 35 | 50 | 20 | 20 | 35 | 100 |
| C | 20 | 20 | 35 | 35 | 20 | 20 | 35 | 35 |
| Ave. | 20 | 30 | 50 | 60 | 20 | 25 | 50 | 110 |

*R*-(*T* & *R*) = Ringer and condenser connected from each side of circuit to ground.
*R*-(*T*) = Ringer and condenser connected from one side of circuit to ground.
*R*-Bridged = Ringer bridged across circuit, no ground connection.
2-*R* (*T*) = 2 Ringers with their associated condensers connected from one side of circuit to ground.
(1) = Before rectifier was cut in.
(2) = After rectifier was cut in.

The measurements on the private-branch-exchange trunk circuits also showed an increase in the order of 125 per cent, but with the exception of three cases this increase was not sufficient to impair the telephone service seriously. In these three cases it was found practicable to take care of the noise by rearrangements in the telephone plant.

On the day the Bridgeport rectifier was cut into service, complaints were received from a number of telephone subscribers on account of the noise. The private-branch-exchange subscribers were the first to report the interference which in most cases was due to the large increase in the noise obtaining before the central office operator answered. This noise was greatly reduced, however, after the connection was completed. In order to reduce the noise level on some of the other circuits it was necessary to clear up some slight unbalances in the telephone plant which would not have had an appreciable effect with the rotating generating equipment furnishing the power.

There were no appreciable effects noted on the Bridgeport-Stratford interoffice trunk circuits.

When the Stratford rectifier station was put into service there was no appreciable effect noticed on the telephone circuits in Bridgeport except for a small area near the exchange boundary along Stratford Avenue, but in Stratford, especially along Stratford Avenue between the two rectifier stations as shown in the shaded area on Fig. 1, the noise effects were greatly increased and the reactions from the telephone subscribers more serious. The Bridgeport-Stratford interoffice trunk circuits, however, showed no appreciable effects.

After this installation three times as many complaints were received from telephone subscribers as were received when the Bridgeport station was installed. Most of these complaints were from party-line subscribers.

Table II gives a general idea of the noise conditions before and after the Stratford rectifier was installed as well as the results obtained after installing a filter in the railway circuit.

TABLE II

| Location Stratford | *R*-(*T* & *R*) | | | *R*-(*T*) | | | *R*-Bridged | | | 2-*R* (*T*) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| A | 20 | 325 | 150 | 75 | 500 | 300 | 20 | 300 | 125 | 75 | 800 | 450 |
| B | 20 | 100 | 65 | 35 | 200 | 85 | 20 | 100 | 65 | 35 | 275 | 125 |
| C | 20 | 35 | 35 | 35 | 75 | 35 | 20 | 35 | 35 | 20 | 110 | 50 |
| D | 20 | 100 | 75 | 35 | 200 | 100 | 20 | 85 | 75 | 35 | 350 | 200 |
| Ave. | 20 | 140 | 80 | 45 | 245 | 130 | 20 | 130 | 75 | 40 | 385 | 205 |

(1) Power from old generating station.
(2) Mercury arc rectifiers at Bridgeport and Stratford.
(3) Same as (2) but with rectifier and filter at Stratford.

## Wave Analysis

A wave analysis of the noise experienced showed 360,- 720,- and 1080-cycle components with the 360 cycle the most prominent. This latter is the fundamental frequency, in this instance, of the ripple in the rectified d-c. voltage wave and is equal to the product of the fundamental frequency of the supply line (60 cycles) and the number of secondary phases of the rectifier (6 phases).

The amount of these harmonic currents flowing over the railway distribution system is a function of the harmonic e. m. f. generated and the load characteristic of the system. Under these conditions, the most practicable means of limiting the flow of these disturbing harmonics on the railway system, and by so doing limiting their interfering effect on the telephone circuits, was to install a filter on the load side of the rectifier. This means of reducing the disturbing harmonics has been used to advantage in other places where the railway current is obtained from mercury arc rectifiers.

## Filter Equipment

The first filter equipment installed in the Stratford substation was only temporary, but similar electrically to the proposed permanent equipment which was in the process of manufacture for both substations.

The equipment consists of a 0.7 millihenry series reactor inserted in the negative return circuit at the station. This reactor acts as a choke to the harmonic currents and of course must be able to carry the entire load current furnished by the station. There are also three resonant shunts connected between the positive and negative sides of the railway circuit on the load side of the reactor in order to by-pass harmonic current at 360, 720, and 1080 cycles, thereby reducing the voltages applied to the line at these frequencies. Each of these resonant shunts has a 2 millihenry air-core coil in series with a bank of condensers. Tuning is accomplished at each frequency by varying the capacity until the harmonic line voltage is a minimum. The capacities obtained for resonance were 105, 28, and 12 $\mu$f., respectively. The condenser banks are built up of 1 $\mu$f. units made to withstand 600 volts direct current indefinitely. See Fig. 3.

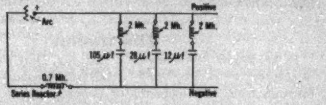

Fig. 3

## Results of Filter Installation

The effect of the filter on the noise levels in the telephone circuits in the Stratford exchange area was quite appreciable and the complaints from the telephone subscribers dropped to only a few cases in the shaded area along Stratford Avenue. The noise measurements obtained are shown in column 3 of Table II. Measurements made with the temporary filter installed in Stratford indicated that a large part of the remaining noise, given under column 3, resulted from the unfiltered rectifier at Bridgeport. It is expected that when a filter is also installed in the Bridgeport substation a further reduction in the noise levels in this particular area will be obtained.

## Conclusion

The magnitude of the interference from a given source, in this case the mercury arc rectifier, depends on the distribution and type of plant of both the street railway system and the telephone system. As shown in Tables I and II, this is clearly indicated by the more serious reactions obtained on the same types of telephone circuits in the Stratford area than in the Bridgeport area. The type of rectifier installed in both areas is the same, but in the Stratford area a larger percentage of the telephone plant is in aerial cable construction with more joint pole line construction with the railway circuits than in the Bridgeport area, where the degree of exposure between aerial telephone and street railway circuits is relatively small.

From the experience obtained with the installation of the six-phase mercury arc rectifiers for the street railway system in Bridgeport and adjacent territory, it can be definitely stated that in general a street railway system energized by mercury arc rectifiers possessing no means of limiting the harmonic components has a greater inductive influence on neighboring communication circuits than when energized by rotating equipment. General experience has shown, however, that by means of properly designed filtering apparatus installed on the d-c. load side of the rectifier, the inductive influence of such a rectifier may be reduced to a level comparable with that of rotating equipment of good wave shape.

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## Discussion

**P. W. Blye:** In connection with Mr. Daly's paper, it may be of interest to outline briefly interference conditions which have resulted from the operation of mercury arc rectifiers on street railway systems in other locations and to describe the work which has been done jointly by the telephone company and the electrical manufacturers in an effort to provide satisfactory measures for reducing these effects. In all cases of interference which have been investigated so far, the a-c. supply systems have been in underground cable or have not been involved in telephone exposures. The interference has therefore resulted from harmonics in the output side of the rectifier only.

As pointed out in Mr. Daly's paper, the ripple in the output voltage of a mercury arc rectifier consists of a fundamental component and its harmonics, the frequency of the fundamental being equal to the product of the frequency of the supply system and the number of secondary phases. In the case of a six-phase rectifier operating from a 60-cycle supply system, the principal alternating components in the output voltage and current, from the standpoint of inductive coordination, would therefore be a fundamental having a frequency of 360 cycles and its second and third harmonics having frequencies of 720 and 1080 cycles respectively. From measurements made on a number of 600-volt rectifiers in the field, the average magnitudes of these three components have been found to be as follows:

| | |
|---|---|
| 360 cycles | 32 volts |
| 720 cycles | 8 volts |
| 1080 cycles | 3.5 volts |

The a-c. components impressed on the trolley and feeder system by a rectifier are, of course, a function of the above voltages and the impedance of the system. The impedances of the systems investigated so far have been found to be inductive reactances which tend to suppress the higher frequency current components. In a representative location in which severe inductive interference was experienced, the most important a-c. components in the trolley and feeder system were found to be as follows:

| | |
|---|---|
| 360 | 17.5 amperes |
| 720 | 2.0 amperes |
| 1080 | 0.5 ampere |

Experience so far has been chiefly with 6-phase rectifiers. A limited amount of experience with 12-phase rectifiers has indicated that while the inductive effects are less than with 6-phase devices there is an inductive coordination problem here also.

In single substation areas the individual stub-end feeders offer a relatively high impedance to the alternating currents generated by rectifiers. In the case of tie feeders connecting rectifier substations with other stations in which rectifiers or rotating equipment are in operation, however, this terminal apparatus provides a low impedance path for the alternating currents and relatively large currents may be expected in such feeders. A somewhat similar situation exists in the case of single substation areas where main feeder routes are involved. The most serious cases of interference may therefore be expected from tie feeders of this character.

Coordination between exposed telephone circuits and street railway trolley and feeder systems such as these which, of course, employ a ground return, is difficult owing to the fact that power system transpositions are impossible.

During the past year, interference has been experienced from a number of rectifier installations in this country and in Canada. While practically all types of telephone service have been affected, the most serious effects have been noted in the case of interoffice trunk circuits, party-line subscribers' circuits, and private-branch exchange systems.

The severity of the interference, of course, varies considerably with the separation of the power and telephone systems. The most severe effects have been noted on telephone circuits carried in aerial cables on the same poles with the trolley system feeders. Serious effects have, however, been noted in long exposures on similar aerial cables located several hundred feet from the trolley system. In a majority of cases the noise has been found to be due to electromagnetic effects resulting from a-c. components in the feeder system.

In one of the most severe cases of interference, noise was measured on party-line circuits in the affected area of the order of 1000 to 2000 units. On interoffice trunk circuits in this area, noise of from 1500 to 2000 units was observed. A number of P.B.X.'s was also seriously affected and while conditions in these cases were improved somewhat by measures taken in the telephone plant, it was not possible to reduce the noise to a satisfactory level by this means. Several other similar cases of severe interference have been experienced as well as a number of cases of a less acute nature such as those in Bridgeport and Stratford, covered in Mr. Daly's paper.

During the past year cooperative studies have been carried on by the manufacturers and the telephone company on methods of improving the wave-shape of rectifiers. This work has indicated that the most effective arrangement is a filter employing a series reactor and a number of shunt branches tuned to the frequencies of the various alternating components to be suppressed. In such a filter the series reactor must carry the full d-c. output of the rectifier. The shunt condensers must withstand the maximum voltage to be expected on the system. These condensers and the shunt coils must carry continuously alternating voltages generated in the rectifier divided by the reactance of the series reactor.

In one of the cases in which severe interference was experienced the filter arrangement used was the same as the temporary installation at Stratford described by Mr. Daly. This filter proved entirely satisfactory as a means of reducing the interference, the important alternating voltage and current components and, therefore, the induced noise, being reduced in ratios of the order of 10:1. Installations of a generally similar type have been made in other locations, and in each case the telephone circuit noise has been reduced to a level comparable to that experienced with the rotating equipment formerly used.

The permanent filters for the Connecticut rectifiers have only recently been installed and complete measurements of their effectiveness have not yet been made. Preliminary measurements in the Stratford Area indicate, however, a reduction in the noise of approximately 8:1.

The results of the cooperative work so far have indicated that satisfactory coordination can be effected between telephone circuits and the d-c. street railway circuits when the latter are supplied either by rotating equipment or by rectifiers equipped with suitable filters.

**R. G. McCurdy:** Mr. Daly's paper on the effect of mercury arc rectifiers on communication circuits treats the matter of coordination between the street-railway feeders and trolley system, and local telephone circuits. He has shown that it is practicable to coordinate such street railway and telephone systems when mercury arc rectifiers are used as the converting equipment and provided suitable filters are employed with the rectifiers. The matter of the effect of the mercury arc rectifiers on coordination with a-c. supply lines has not been covered.

Inductive coordination difficulties so far experienced by the Bell Telephone Companies with power circuits employing mercury arc rectifiers have been confined to the d-c. side. The a-c. feeders to the mercury arc rectifiers have either been in cable or else in relatively short overhead feeders not involved in any extensive exposures with telephone circuits.

In connection with various tests which have been made on rectifier installations in cooperation with the manufacturers and operating companies, considerable data have been gathered on the effect of the rectifiers on the wave shape of the a-c. system from which it is supplied. This has indicated that the six-phase mercury arc rectifiers take an alternating current having a telephone interference factor, in the case of 60-cycle systems, of from 300 to 500. There are present all the odd non-triple harmonics, being the harmonics immediately below and immediately above the even harmonics appearing on the d-c. side. The experience with 12-phase rectifiers has been less extensive but it is expected that the harmonics and the telephone interference factor will be lower than with 6-phase rectifiers.

The wave-shape distortion introduced into the a-c. voltage wave will, of course, depend upon the impedance of the a-c. system from which the rectifier is supplied. In a large system with comparatively short feeders, the distortion in the voltage wave will be comparatively small. With comparatively long feeders or a system of small size, considerable voltage distortion may be experienced.

Where overhead lines supplying mercury arc rectifier loads are involved in exposures with open-wire telephone lines, the difficulties of inductive coordination will be greatly increased over that experienced with the usual type of load. The degree of difficulty will increase with the increase in voltage and current telephone interference factors caused by the use of the rectifier. This problem is much more likely to be met with in cases of interurban electrifications or electrifications of main line railroads involving a-c. transmission over considerable distances than in street railway installations where the a-c. feeders will more often be in cable.

**J. W. Milnor:** It may be of interest to mention the experience of the Western Union Telegraph Company in connection with interference from installations of mercury arc rectifiers.

These remarks will be confined solely to inductive interference with telephone-circuit operation. We have not yet found any serious interference with the types of telegraph circuit now generally employed in handling the company's business. Our general experience indicates that interference from the trolley (d-c.) side of a rectifier installation is severe to telephone circuits if filters are not employed. Such interference, however, is mitigated considerably by the employment of the type of filter which Mr. Daly described.

Mr. Daly has confined himelf to the discussion of interference from the trolley (d-c.) side, and it is here I think that one's impression might be somewhat misled, if some mention were not made here concerning the other effects. The telegraph company has been concerned with one case where its line is paralleled by both the a-c. and d-c. sides of a rectifier system. The 6th, 12th, and 18th harmonics were found to be reduced by the filters, but the interference remaining was found to be severe at harmonics of the frequency of 5, 7, 11, 13, 17, and 19 times the fundamental (60 cycles). You will note that these frequencies are one harmonic removed above and below the 6th, 12th, and 18th which are characteristic of rectifier operation from a 60-cycle source. I regret that our investigations have not proceeded far enough so that we can present a more detailed discussion of this odd-harmonic induction, possibly to be attributed to the a-c. side of the rectifier system.

Our experience indicates that it is most desirable that further investigation be made so that we may have a better understanding of the matter of proper inductive coordination for rectifier installations. It is to be hoped that manufacturing companies and utilities contemplating the use of rectifiers where communication circuit parallelisms are involved, will give considerable thought to this matter prior to making a choice as to the type of equipment to be used in providing direct current for propulsion circuits.

**O. K. Marti:** In regard to Mr. McCurdy's discussion I should like to mention that interference due to an a-c. line supplying rectifiers is probably to be feared only if the entire load consists of rectifiers. In case the a-c. supply line also furnished power to other apparatus, such as motors, lights, etc., the rectifier load will not produce a distortion of the alternating current to any considerable degree. Since in almost every case some other load is connected to the line supplying a rectifier, this problem does not seem to be so serious. Besides, in cities and larger towns all the supply lines are brought into the substations in cables, which again will eliminate the possibility of interference with communication circuits. Due to the fact that the rectifier load is always a three-phase balanced load, the third harmonic and its multiples are eliminated from the line current by the transformer connections used. There is no residual line current and therefore very little possibility of interference. Further, it might be possible to improve conditions, where interference does exist, by alternately connecting a rectifier in delta and another one in star on the primary side, as this method of connection might filter out some of the harmonics.

**W. B. Hall:** I should like to show an oscillogram, taken at the Congress St. Substation, of the actual waves whose effects the previous speakers have been analyzing.

At very light load, the direct voltage will consist of successive peaks of the six-phase sine waves, as each anode carries the load alone for one-sixth of a cycle. The variation in voltage is from 0.866 to 1.000 or 13.3 per cent.

With heavy load (as shown in the top curve of the oscillogram, Fig. 1), the reactance of the six-phase transformer causes the anode which is carrying the load to continue to supply current, and causes the incoming anode to pick up the current gradually, so there is a period of overlapping during which two anodes are sharing the load. During this period, the direct voltage is as much below the incoming anode's sine wave as it is above the outgoing anode's sine wave, since the outgoing anode is dropping its load at the same rate that the incoming anode is picking it up, and therefore $L \frac{d i}{d t}$ for one equals $L \frac{d i}{d t}$ for the other. Hence the direct voltage follows a line exactly halfway between the two sine waves, as shown in Fig. 2, until the current in the outgoing anode has entirely ceased, when the direct voltage suddenly jumps to the sine wave of the incoming anode. The variation here is more than the 13.3 per cent, the amount depending upon the length of the period of overlap which depends upon the load.

But this is the wave of voltage variation, which could cause interference only by capacity coupling. The effect of capacity coupling at 600 volts is negligible. Most of the interference is by inductive coupling with the direct *current*. This current goes mainly to series motors which are highly inductive and draw a current wave much smoother than the voltage wave (see feeder current in the oscillogram). These oscillograms are all taken without the d-c. filter in service.

FIG. 1

This direct current is supplied successively by each anode in turn. Hence each anode supplies a direct current for 60 deg., then none. The anode current then is one rectangular block 60 deg. long for each cycle (see oscillogram).

The transformer primary current is the same as the anode current. But since the primaries are delta-connected, the line current has two successive anode current blocks in it. Hence the a-c. line current consists of a rectangular wave for 120 deg., then zero for 60 deg. and so on. The curve marked a-c. primary current shows this, superimposed upon the transformer exciting current. These changes in line current are much more severe than the changes in the d-c. wave, and they are not remedied by inductance in the load or by d-c. filters. There would be much more inductive interference from the a-c. line than from the d-c. output, with equivalent exposure. Of course, the exposure of telephone lines to power lines is usually much less than to d-c. feeders and trolley wires.

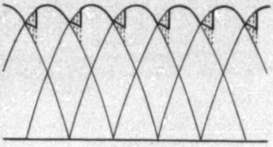

FIG. 2

The oscillogram (a-c. volts) shows the effect of this current wave on a-c. line voltage.

**J. J. Smith:** Mr. Daly points out in his conclusion that the interference from a given source depends on the distribution and type of plant of both the street-railway system and telephone system. The rectifier by nature of the mechanism through which it converts alternating current into direct current gives rise to harmonics in the d-c. voltage wave. If it were possible to obtain a rectifier which did not produce harmonics there would be no problem of telephone interference. On the other hand, even though harmonics are present in the power system, there would again be no problem of this type of telephone interference if the telephone lines were perfectly balanced. The real problem of interference is therefore to reduce the harmonics on the power system and the unbalances on the telephone system as far as is economically practicable.

On making a comparison in Table I under *R*-(*T* & *R*) 2 and 2-*R* (*T*) 1 it will be noted that the average noise units in each case are approximately the same although one set of measurements was made when the rectifiers were operating and the other set before the rectifiers were cut in. It will also be noted that with the rectifiers operating the average noise units in the telephone lines varied 3 to 1 due to the different degrees of balance in the telephone circuit.

While in theory any desired reduction in the 360-, 720-, and 1080-cycle components may be obtained by the use of reactors and resonant shunts, the addition of such equipment adds to the costs of the rectifier and the d-c. reactor introduces losses into the circuit, lowering the efficiency. It is, therefore, undesirable to make this apparatus any greater than is absolutely necessary.

Thus it would appear that the problem of interference from mercury arc rectifiers is a mutual one between the telephone engineers and the power engineers. The telephone engineers can reduce the noise considerably if they find means to take care of the unbalanced arrangement of selective ringers referred to in the paper, under 2-*R* (*T*) for instance, while the power engineers can assist in the reduction by the addition of filtering equipment.

It would be very interesting if Mr. Daly would amplify his paper slightly to give some idea of the exposures of the telephone lines to the trolley lines. I assume that the difference in noise units at different points is due to the different exposures of the telephone lines. In order to bring the data into a form in which they might be used for comparison with other rectifier installations, it would also be necessary to give the magnitude of the harmonics in both the voltage and current in the d-c. wave form of the rectifier.

In Fig. 3 in the paper the capacities and inductances given do not tune for the 6th, 12th, and 18th harmonics of 60 cycles. I find on checking up that the points at which they tune are 347, 675, and 1030 cycles. This is probably due to the fact that the coils are only approximately 2 millihenries. It might be well, however, to state this as it might lead to some confusion in the minds of persons reading the paper.

**C. J. Daly:** I feel that Mr. Marti is unduly optimistic as to the effect of reducing the harmonics by means of other loads connected to the a-c. line supplying a rectifier. It would be necessary that the impedance of such loads be small as compared to the impedance of the transmission line or feeder in order to produce any large reduction in the magnitude of the harmonic components transmitted over the line or feeder. It is also essential that the telephone exposure should not be located between the rectifier and these low-impedance loads.

In reference to the discussion by Mr. Hall, experience has shown that the induction from the d-c. side arises principally from the current harmonics. While these currents are small compared to the load current, as indicated by the oscillogram shown by Mr. Hall, the inductive effects are proportional to the magnitude of the harmonic components and not proportional to their values relative to the d-c. load current. As will be noted from the various values given in Mr. Blye's discussion, values of 360 cycles of the order of about 18 amperes have been noted when filters were not employed in the d-c. side.

I am somewhat uncertain as to the meaning of the term "equivalent exposure" used in Mr. Hall's discussion. It is evident, however, that if the a-c. feeders consisted of one wire with rail return as in the case of the d-c. side, the interference from the a-c. side would be much more severe.

Mr. Smith's assumption that the difference in the noise values experienced on the telephone circuits was due to the difference in the degree of exposure is correct. For example, in the case of the telephone circuit to the *A* location on which 800 noise units were experienced, the exposure was much more severe than in the case of the telephone circuit to the *C* location where 110 noise units were obtained. The former circuit is in underground construction which parallels the railway tracks for about one-quarter mile and then extends in aerial cable for a distance of about one-half mile on the same pole line with both positive and negative railway feeders. The latter telephone circuit is approximately one-half mile in length, entirely in underground cable construction with an exposure of about one-quarter of a mile to the railway tracks.

In reference to the resonance points of the capacities and inductances, it may be pointed out that the coils are only approximately 2 millihenries and the capacitance values given are in terms of the nominal values of the condenser units. The actual capacitance may vary from these nominal values in the order of one per cent. As explained in the paper the branches were adjusted to be in resonance at the actual frequencies of the various harmonics to be reduced.

# Rocky River Hydroelectric Development
## Of The Connecticut Light and Power Company

BY E. J. AMBERG[1]

Associate, A. I. E. E.

***Synopsis.**—This paper describes the Rocky River hydroelectric development of the Connecticut Light and Power Company, near New Milford, Connecticut, which is a storage development for regulating the Housatonic River below New Milford.*

*There are no sites on the main river suitable for a large storage reservoir. It was therefore necessary to select a site on a tributary, the Rocky River. The run-off from the natural drainage area of the reservoir basin furnishes only a part of the water required to fill the reservoir, making it necessary to pump the balance from the Housatonic River against a maximum head of 240 ft. This is the first large application of pumped storage in the United States which accounts for the general interest shown in the Rocky River development.*

*The first part of the paper deals with the factors which have to be considered in determining the economic possibilities of such a development. The second part of the paper is a description of the main features of the development itself.*

* * * * *

THE Rocky River hydroelectric development of the Connecticut Light and Power Company has created considerable interest among technical as well as non-technical men, as a project for regulating the flow of the Housatonic River below New Milford, Connecticut. Briefly, the development consists of a storage reservoir created on Rocky River, a tributary of the Housatonic, with a power and pumping plant on the Housatonic River; the power and pumping plant being connected by a single penstock with the reservoir.

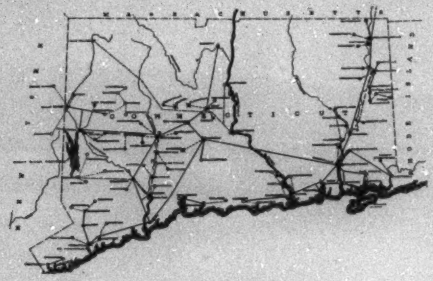

FIG. 1—MAP OF CONNECTICUT

Showing the system of the Connecticut Light and Power and Associated Companies, and their interconnections

■ Generating stations (steam)
□ Other companies' generating stations (steam)
▲ Generating stations (hydro)
△ Other companies' generating station (hydro)
● Communities supplied retail
○ Other companies supplied
⊗ Gas and electricity supplied
+ Gas supplied
——— Transmission lines
— - — Other companies' transmission lines
- - - - - Distribution lines
. . . . . . Other companies' distribution lines

Fig. 1 shows the location of the Rocky River development in relation to the system of the Connecticut Light and Power Company and its associated companies. Fig. 2 shows, on an enlarged scale, the vicinity of the Rocky River development. The Rocky River basin is located north of Danbury and west of the Housatonic River, and the site of the development is approximately 1½ mi. by state highway from the nearest railroad station at New Milford. The basin has a drainage area of approximately 40 sq. mi., eight and one-third of which are covered by the storage lake. The branches of the Rocky River heading near Danbury flow north to meet the branch of the river which heads near Sherman and flows in a southerly direction. From the junction of these branches, the river flows north through marshy flats which form the bottom of the reservoir, to a point 2½ mi. from the junction of the Rocky River with the Housatonic, wherein Rocky River falls about 200 ft. over a rocky bed. The shores of the reservoir are for the most part steep and rocky, rising to elevations of from 500 to 1000 ft. They are well covered with second growth timber together with some virgin timber in the more inaccessible locations.

The unusual features of this development lies in the fact that the drainage area of the reservoir basin will supply only about 1.5 billion cu. ft. of water in an average year while the useful capacity of the reservoir is 5.9 billion cu. ft. All water above the natural run-off required to fill the reservoir must be pumped from the Housatonic River against a head varying from 200 to 230 ft. While considerable excess hydro energy will be available for pumping, the studies and investigations for this development are all based on using secondary steam energy for pumping, to be supplied from the

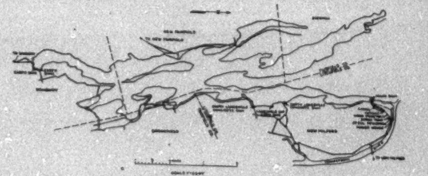

FIG. 2—OUTLINE MAP OF ROCKY RIVER RESERVOIR

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*Presented at the Northeastern District No. 1 Meeting of the A. I. E. E., New Haven, Conn., May 9-12, 1928.*

Devon steam station of the Connecticut Light and Power Company.

The Rocky River reservoir may be likened to a large storage battery. Charging the battery is accomplished by secondary steam energy from Devon driving two 8100-hp. centrifugal pumps, delivering water to the reservoir. The battery is discharged by means of the 30,000-kv-a. generating unit delivering primary hydro energy.

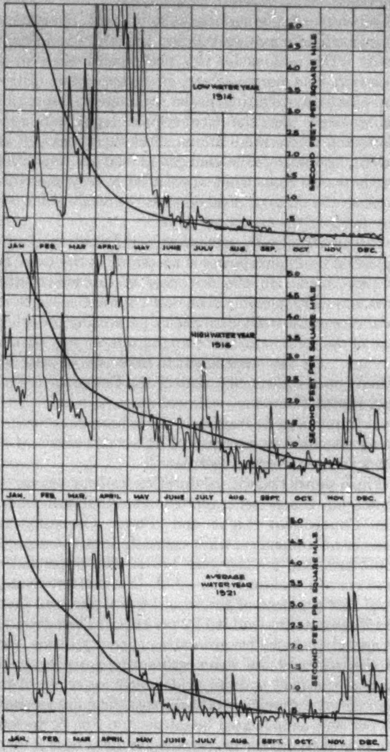

FIG. 3—HYDROGRAPHS OF THE HOUSATONIC RIVER

Showing hydrographs and superimposed flow duration curves for a low water year, a high water year, and an average water year

The efficiency of this storage battery for changing secondary steam energy into primary hydro energy is 61 per cent; this includes all losses from the 66,000-volt bus at the Devon Steam Station through the pumping units into the reservoir and back through the generating unit to the 66,000-volt Rocky River bus. In other words, for every 100 kw-hr. supplied by the Devon Steam Station in filling the reservoir, 61 kw-hr. are delivered by the Rocky River generating unit, when the water is drawn out again. We must not, however, overlook the fact that below the Rocky River plant there is an additional total average head of 191 ft. available, of which 71 ft. is efficiently developed at Stevenson. If the head at Stevenson is added, then for every 100 kw-hr. of steam energy, 79 kw-hr. of hydro energy are returned. If the total head from Rocky River to tide-water is added, 111 kw-hr. of hydro-energy could be obtained from every 100 kw-hr. of steam energy used in pumping.

Before going into a more detailed description of the Rocky River project, it is desirable to review, briefly, two factors which are essential to understand the basis upon which Rocky River has been developed. These two factors are: the hydrology of the Housatonic River, and the general character of the system load curves of the Connecticut Light and Power Company.

It is generally known that the rivers in the eastern part of the country have a very irregular flow, unless some natural or artificial means exists for regulation. The Housatonic River, with which we are concerned, had no means of regulation; the stream flow shows very wide variations, as can be seen from Fig. 3, showing hydrographs and duration flow curves for a typical wet, average, and dry year. From the hydrographs, it is quite evident that the only period of the year when any reliance can be placed on the river flow is in the Spring-time. The rest of the year the flow is quite irregular. While frequently a somewhat larger flow may be ex-

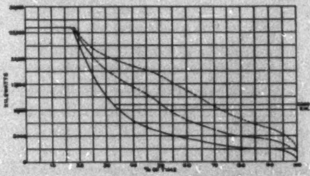

FIG. 4—POWER DURATION CURVES FOR THE COMBINED OUTPUT OF BULLS BRIDGE AND STEVENSON STATIONS WITHOUT REGULATION BY ROCKY RIVER DEVELOPMENT

Typical low water year 1914..................
Typical high water year 1916..................
Typical average water year 1921..................

| | Drainage area | Net head in ft. | Kw. per cu. ft. per sec. | Installed capacity |
|---|---|---|---|---|
| Bulls Bridge........ | 782 sq. mi. | 104 | 6.27 | 7,200 kw. |
| Stevenson.......... | 1510 sq. mi. | 71 | 4.40 | 18,750 kw. |
| | | | | 26,000 kw. approx. |
| Rocky River........ | 35 sq. mi. | 214.2 av. | | |
| | | Power— | 15.55 | |
| | | Pumping | 25.35 | |

Regulation by Rocky River development to produce 11,000 kw. firm 24-hr. capacity, expressed in kw-hr.

| | Low water year | High water year | Av. water year |
|---|---|---|---|
| Rocky River output | 31,100,000 kw-hr. | 7,400,000 kw-hr. | 17,400,000 kw-hr. |
| [1]Stevenson output | 8,800,000 kw-hr. | 2,100,000 kw-hr. | 4,900,000 kw-hr. |
| Total output...... | 39,900,000 kw-hr. | 9,500,000 kw-hr. | 22,300,000 kw-hr. |

1. Generated at Stevenson on water discharged from Rocky River

pected in the Fall, there is no certainty of it, as shown for the dry year, where the low water condition continued right to the end of the year. With the river plants at Stevenson and Bulls Bridge operated in conjunction with the Rocky River storage plant the 24 hr. firm power of the hydro system is 11,000 kw. Fig. 4 shows the unregulated power duration curves for a typical dry, wet, and average year, limited by the installed capacities of the Stevenson and Bulls Bridge stations which together total 26,000 kw. The regulated 24 hr. firm power of 11,000 kw. obtained by the addition of Rocky River is also shown. The respective areas between the 11,000 kw. regulated firm power and the power duration curves represent the energy which has to be furnished from storage. The amount required in each year varies considerably, being 9,500,000 kw-hr. in the wet year and 39,900,000 kw-hr. in the dry year. Of these amounts, 78 per cent is produced by the Rocky River station and the balance at Stevenson, generated from the water released from Rocky River station.

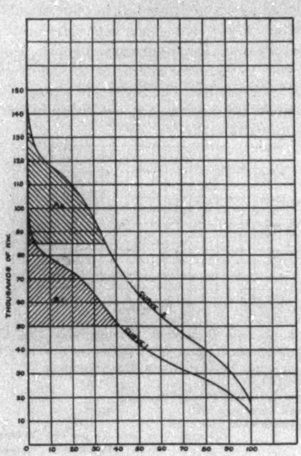

FIG. 5—LOAD DURATION CURVES

| | Curve No. 1 | Curve No. 2 |
|---|---|---|
| Max. kw-hr | 100,000 | 150,000 |
| Load factor | 47.3% | 47.3% |
| Hydro kw | 50,000 | 65,000 |
| Increase | | 15,000 |
| Hydro load factor | 17.2% | 13.2% |

Hydro area $A_1$ = hydro area $A_2$

By applying the 24-hr. firm power of 11,000 kw. to the upper half of the load curve, as shown in Fig. 5, curve 1, the total installed hydro capacity of 50,000 kw. can be used as firm capacity. Before regulation by Rocky River, the combined firm capacity of the Stevenson and Bulls Bridge stations was only 10,000 kw. although the installed capacity was 26,000 kw. Therefore, by installing a 24,000-kw. generating unit in the Rocky River station and by regulating the river the firm hydro capacity has been increased by 40,000 kw.

To obtain maximum benefit from such a storage development, it is necessary to apply it to that part of the load requiring the smallest number of kilowatt hours. This brings us to the second factor, the load curves.

When plotting system loads in the form of an annual duration load curve we will find that there is a decided peak. The reasons for this pronounced peak on the duration load curves, vary; in metropolitan districts the short-time lighting peaks are largely responsible; on systems like the Connecticut Light and Power Company where there are no short time peaks, of any extent, the seasonable changes in load are responsible. In the latter case, what appears as a very short-time peak on the duration load curve is the result of the 9-hr. day loads of the maximum days.

It can readily be seen that a different method of applying the hydro power is necessary in the two cases of peak load. In the first case of the metropolitan area, a weekly, possibly even daily, storage capacity will take care of the individual peaks, permitting the utilization of the river for actual demand without any seasonal storage. On the other hand, to take care of peak conditions on a system like that of the Connecticut Light and Power Company, seasonal storage in addition to weekly pondage is required. This seasonal storage is being provided in our case by the construction of the Rocky River storage reservoir.

Fig. 5 shows two annual duration load curves; curve 1 represents the present approximate combined load of the Connecticut Light and Power Company and associated companies, while curve 2 shows the expected combined load for the year 1931. The upper half of load curve 1 and load curve 2 for that matter, contains only 18.2 per cent of the total kw-hr.; the load factor of this part of the load is 17.2 per cent. The advantage of applying the hydro generating capacity to the peak of the load and the steam generating capacity to the base of the load is quite evident from a study of this load curve. Assuming that the total load has increased 50 per cent as indicated by curve 2 on Fig. 5, the same number of hydro kw-hr. represented by area A 2 would permit a firm hydro capacity of 65,000 kw. as against 50,000 kw. firm capacity of curve 1; or 15,000 kw. firm capacity could be installed without increasing the storage facilities. Additional capacity can often be installed at a low cost per kilowatt in existing plants, thus lowering the average unit cost per kilowatt of hydro capacity.

Such a storage development as Rocky River has therefore some inherent values which can be increasingly realized as the load increases.

Aside from the features discussed above, hydro plants have another great advantage in that they provide standby capacity which can be made available in a fraction of the time required at a steam station, because to get up steam and warm up a turbine requires time unless boilers are kept in service and excess turbine capacity is kept on the line to take care of sudden load demands.

With the means of regulating the stream flow below Rocky River, it will be possible to develop the full head on this section of the river, which will then produce a total 24 hr. firm power of approximately 23,000 kw.

The hydro capacity will again be applied to the upper half of the load curve, which from curve 1 on Fig. 5 shows a load factor of 17.2 per cent. In order to take care of possible changes in the load curve we will make an arbitrary increase in the load factor of one-third, which will change this load factor to 23 per cent. With a 23 per cent load factor and a 24 hr. firm power of 23,000 kw. it will be possible to increase the total installed hydro capacity to 100,000 kw. by developing the full head of the river between tide-water and Rocky River.

The second 24,000-kw. unit at Rocky River is in addition to the 100,000-kw. capacity above referred to; its main function will be to act as a spare unit, which can be made instantly available. The second unit can be installed at a low unit cost including the raising of the reservoir level which will add approximately one billion cubic feet to the useful storage capacity.

From the above can be seen that the Rocky River development has a considerable increased future value, by making it possible to develop the full head below Rocky River as the load of the system of the Connecticut Light and Power Company and associated companies increases. Without Rocky River further economic development of the river would have been impossible.

In concluding the first part of this paper an account of water utilization at Rocky River and Stevenson stations for a typical average year seems in order.

As stated before with a full reservoir the water level will be at elevation 430 ft. The normal allowable draw-down is 30 ft., or to water level elevation at 400 ft. In this 30 ft. of draw-down, 5.9 billion cubic feet of water are taken from the reservoir. This amount of water, in going through the Rocky River generator will produce 24,200,000 kw-hr.

From the power duration curve for an average year in Fig. 4, it will be seen that 22,300,000 kw-hr. must be generated by water from Rocky River to maintain the 24 hr. firm power of 11,000 kw. Of the total of 22,300,000 kw-hr. the Rocky River station will furnish 17,400,000 kw-hr. while the remaining 4,900,000 kw-hr. are generated at the Stevenson station by the water discharged from Rocky River station. The amount of water that must be taken from the reservoir in order to produce 17,400,000 kw-hr. at Rocky River station is approximately 4030 billion cu. ft., based on an average figure of 15.55 kw. per sec. ft.

The water used for refilling the reservoir falls into two classes with two subdivisions in each class.

1. Run-off water from the Rocky River drainage area; this is subdivided into

   a. Water held back at a time when it would have spilled over the Stevenson dam.

   b. Water held back at a time when it could have been used at the Stevenson station.

2. Water taken from the Housatonic River and pumped into the reservoir, subdivided into

   a. Water taken from the Housatonic River at a time when this water would have spilled over the dam at Stevenson.

   b. Water taken from the river at a time when this water could have been used at the Stevenson station.

The following is a brief summary of the amount of water obtained from each subdivision for an average year.

1. The run-off from the Rocky River drainage area in an average year based on a net area of 35 sq. mi. is 1.6 billion cu. ft.

   a. The daily discharge records for the average year show that there are 58 days of the year when the flow of the river equals or exceeds 2.86 cu. ft. per sec. per sq. mi., the flow necessary to produce 24 hr. full-load at Stevenson. The run-off during the 58 days amounts to 0.84 billion cu. ft. This amount of water, when finally released from the reservoir will utilize the additional head at Rocky River as well as at Stevenson.

   b. The difference, or $1.6-0.84 = 0.76$ billion cu. ft., is Rocky River run-off that is caught in the reservoir at a time when the river flow was less than 2.86 cu. ft. per sec. per sq. mi. This amount of water, when finally released, will utilize the additional head of the Rocky River station only.

2. The total amount of water to be pumped in an average year is $4.03-1.6 = 2.43$ billion cu. ft. The possible number of pump hours per week with two pumping units available is 336 hr. Load conditions, however, will normally limit the actual pump hours per week to 200 hr. which corresponds to an average pumping rate of 298 cu. ft. per sec. as against the maximum possible rate of 500 cu. ft. per sec., which is the capacity of the two pumps.

   a. The daily discharge records for the average year show that there are 58 days of the year when the flow of the river equals or exceeds 2.86 cu. ft. per sec. per sq. mi., the flow necessary to produce 24 hr. full-load at Stevenson, and 45 days when the river flow equals or exceeds 3.16 cu. ft. per sec. per sq. mi., the flow necessary to produce 24 hr. full-load at Stevenson after an average of 298 cu. ft. of water per sec. has been taken from the river at the Rocky River station. The amount of water pumped during this period is 1.32 billion cu. ft. This water when released from the reservoir will utilize the additional head at the Rocky River and Stevenson stations.

   b. To completely fill the reservoir, an additional amount of $2.430-1.325 = 1.105$ billion cu. ft. of water must be pumped at a time when the river flow is less than 2.86 cu. ft. per sec. per sq. mi. This water when released from the reservoir will utilize the additional head of the Rocky River station only.

TABULATION SHOWING SUMMARY OF WATER USED FOR FILLING THE ROCKY RIVER RESERVOIR IN AN AVERAGE YEAR

| Classification | Water | Amount of water billions of cu. ft. | Will use "additional" head of Rocky River station | Will use "additional" head of Stevenson station |
|---|---|---|---|---|
| 1 (a) | Run-off exceeding full-load flow | 0.840 | Yes | Yes |
| 1 (b) | Run-off below full-load flow | 0.760 | Yes | No |
| 2 (a) | Pumped water exceeding full-load flow | 1.325 | Yes | Yes |
| 2 (b) | Pumped water below full-load flow | 1.105 | Yes | No |
|  | Total | 4.030 |  |  |

## DESCRIPTION OF THE ROCKY RIVER DEVELOPMENT

*Reservoir and Dams.* The storage reservoir or lake is about 10 mi. long and 1¾ mi. across at the widest part. It has a surface area of 8⅛ sq. mi. and a shore line of approximately 60 mi. The creation of a lake of this size made it necessary to abandon and relocate highways and homes. Approximately 31 mi. of highway were abandoned and 9¼ mi. of new and relocated highway were built. Six cemeteries were relocated. Outside of several summer colonies located around the four ponds included in the basin, only 35 families with permanent residences were affected by the construction of this reservoir, which is an unusually small number considering the area covered. The bottom of the reservoir was for the most part swampy ground, and 4500 acres were covered with woods.

The main dam is located across Rocky River at a point about one mi. above its junction with the Housatonic River. It is an earth filled dam with a core wall. The lower part of this core wall consists of a two ft. concrete section which extends on the average ten feet above and an average of five feet below the ground surface. On top of this concrete section was placed a six in. Wakefield core wall (timber) reaching up to elevation 435 ft. On the west end, the concrete core wall was located in solid rock. This rock, however, dropped off rapidly below the surface at the location of the old river bed; from this point the core wall continued in earth. Fig. 6 showing a cross-section and plan of the dam gives a better idea of its construction than a lengthy detail description.

To take care of Rocky River during the construction of this dam a concrete conduit approximately 4 by 5 ft. was located near the original river bed. A small auxiliary earth dam with wooden sheet piling was erected across the river bed near the entrance to this concrete conduit, to create a small pond from which water could be pumped for the sluicing operation. The intake to this concrete conduit was equipped with a heavy wooden gate hinged at the top, used for closing off the flow through the conduit after completion of the dam. The material for the dam was obtained from the canal excavation, and was placed in the dam by sluicing. The relative elevations were such that only a very small quantity could be sluiced directly. So practically all of the material was excavated with drag lines and placed into large piles. It was then sluiced from these piles down into the dam. However, after the dam had reached a certain height, the slope in the sluicing line became insufficient; this was partly due too, to the increased distance of the drag line from the dam. When this point was reached the material was sluiced to a pumping plant located at elevation 375 ft. Before being delivered to the pumps, the material was passed through a revolving screen which eliminated all stone over 6 in. in diameter.

On the dam itself, a gasoline driven drag line was utilized to throw up small dikes on each edge to hold the water within the dam and give the sluiced material a chance to settle. Near the center of the dam was a concrete chimney with openings which acted as overflows for the sluicing water. The chimney connected at the bottom with the concrete conduit under the dam. As the dam came up the openings were closed up. The dike along the canal was constructed in a similar manner, as it constitutes practically an extension of the main dam.

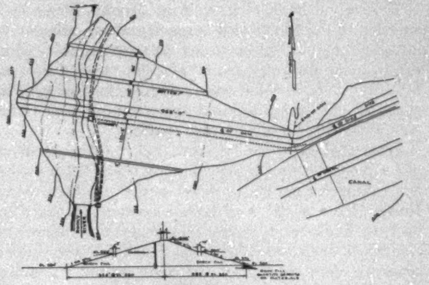

FIG. 6—PLAN AND CROSS-SECTION OF THE MAIN EARTH DAM

To take care of some low points in the rim of the basin five smaller dams were necessary. Two of the dams are near Danbury. Both are earth dams of the same general design as the main dam. The material for these dams had to be hauled in as there was no water available for pumping the material from the borrow pits. It was wetted down and rolled. The other three dams are located near Lanesville. The north and south Lanesville dams are constructed of concrete. The so-called Lanesville Gap was closed by an earth dam similar in design to the main dam. Seamy rock at the west end of this dam presented considerable difficulties in obtaining a tight job. The concrete section on which the 6 in. Wakefield core wall rested was considerably enlarged; in addition a considerable number of grout holes was put in the rock. The material was placed in this dam by sluicing.

The crest of the main dam and the Danbury dikes is at elevation 442 ft., or 12 ft. above the present normal maximum reservoir level at elevation 430 ft.

The crest of the dike at the Lanesville Gap is at elevation 440 ft. or 2 ft. lower than the crest of the main dam. This dike is located in a cove which practically eliminates all wave action, which accounts for the 2 ft. lower crest.

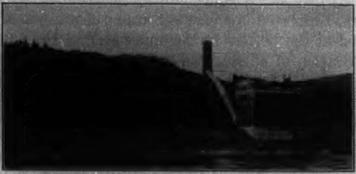

Fig. 6a—General View of Power House Penstock and Substation

The present crest of the concrete section of the South Lanesville dam is at elevation 432 ft. and of the North Lanesville dam at elevation 431 ft. Each of these concrete dams is so designed that the concrete sections can later be raised four feet at a nominal cost. This construction would be done in order to raise the level in the reservoir from 430 ft. to 435 ft., which would add approximately one billion cubic feet to the reservoir. The future maximum water level in the reservoir is 440 ft., or an increase of 10 ft. over the present level. However, to raise the level to 440 ft. would require considerable additional construction work.

*Intake.* The canal leading from the reservoir to the intake was excavated for about 3300 ft. along the east bank of the valley. Terminating the dike in the side hill permitted the construction of a circular intake tower in the canal with only a short length of concrete conduit extending through the dike. Six equal intake openings are located in the half of the tower facing the canal. Each opening is protected by vertical trash racks provided with a compressed air rack raking device, and each opening can be closed by steel stop logs operated by means of manually operated hoists. A self-closing sliding Broome gate is located at the entrance to the concrete conduit in the tower and operated by electric hoist. Ample air-vents to the penstock are provided in the intake structure back of the gate. Necessary by-pass pipe connections are provided to fill the penstock from the intake with the Broome gate closed, and for filling the intake from the canal with the steel stop logs in position.

*Penstock.* The concrete conduit, having an inside diameter of 16 ft., extends only a short distance from the intake tower to the wood stave pipe line. This wood pipe line has an inside diameter of 15 ft. and extends for approximately 1007 ft. along the hillside. The average gradient is 0.5 ft. in 100 ft. The intake tower and wood pipe line are of sufficient capacity for the installation in the future of a second generating unit. The wood pipe line joins a steel penstock *Y*-connection; one of the two branches is blanked off ready for a second penstock for the future unit, while the other extends a short distance to a Johnson differential surge tank. Freezing of the water in this surge tank is prevented by agitation with compressed air. The compressed air pipe line follows the penstock from the power house, branching off at the surge tank, and on up to the intake for the air raking device, as previously mentioned. From the surge tank the penstock drops down the hillside to the power house (Fig. 6a). The inside diameter varies from 13 ft. to 11 ft. just outside the power house, where there is another *Y*-connection, one branch for the generating unit and the other for the two pumping units. Each branch has a Venturi section for measurement of flows. Fig. 7 shows the general layout of the penstock.

*Power Station Building.* Like most modern power house construction, the substructure of Rocky River plant is built exclusively of concrete, with a small amount of steel work to support the lighter floors. The foundation rests on bedrock, which was so close to the elevation desired, that little rock had to be taken out or extra concrete put in. The concrete barrel type of construction was used, wherein the entire weight of generator, shaft, runner, and hydraulic thrust is carried through a concrete barrel and the turbine speed ring, to the foundations. The south end of the building, referred to as the switch bay, is supported on reinforced concrete columns. All the surface of the concrete substructure was coated with a water-proofing compound.

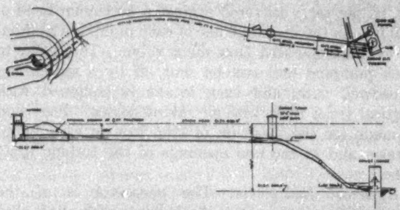

Fig. 7—Plan and Profile of the Pipe Line and Penstock

The power house superstructure is of structural steel framework and brick. Precast gypsum slabs provide the foundation for an asphalt built-up roof. All exterior trim of the building is of precast cement blocks.

There are four floors in the switch bay with a control cable terminal room below the first floor. The first floor is the control room with the switchboard. The second floor contains the 13,200-volt pump motor bus and switching, and the third and fourth floors are used for the 4600-volt distribution bus and storage battery room.

*Hydraulic Equipment.* The hydraulic equipment of the power station consists of one 33,300-hp. vertical shaft turbine and two 8100-hp. vertical shaft centrifugal pumps. A noteworthy feature of the turbine is the cyclinder gate which replaces the more conventional Butterfly or Johnson valves for directly shutting off the flow of water to the turbine. This cylinder gate is built in the turbine in the annular chamber between the pit liner and the speed-ring. It is operated from a valve on the generator floor which controls the admission of water under penstock pressure to the annular chambers above the valve. Positive mechanical locking devices hold the valve in either a full, open, or closed position.

The turbine is equipped with a 110,000 ft. lb. actuator governor located on the generator floor, arranged to operate the turbine gates by two cylinders in the turbine pit. Oil is supplied to the governor system at 200 lb. per sq. in. by an a-c. motor driven screw pump. The governor of this unit consists of a centrifugal speed element driven by a synchronous motor.

The centrifugal pumps, as far as I could find out, are the largest in the United States. The pump specifications called for a rating of 112,500 gal. per min. (250 cu. ft. per sec.) delivered against a maximum head of 240 ft. In the discharge line of each pump is a hydraulic cylinder operated Dow pivot valve. The intake to each pumping unit can be shut off by a self-closing Treadwell gate, and each intake is equipped with vertical trash racks with air raking device. Provision is made for the insertion of stop logs in each pump intake, and in the two openings of the turbine draft tube.

*Electrical Equipment.* The generator is of the standard vertical water-wheel type with shaft end exciter. It is rated at 30,000 kv-a., 80 per cent power factor, 13,900 volts, 3-phase, 60 cycle, 200 rev. per min., with direct connected exciter rated at 154 kw., 250 volts, compound wound with interpoles. The pump prime movers are vertical synchronous motors rated at 7900 kv-a., 80 per cent leading power factor, 13,200 volt (with voltage range of 5 per cent above or below) 3-phase, 60 cycle, 327 rev. per min. Pump motor and spare excitation is furnished by two motor-generator sets each consisting of a 150 kw., 1200 rev. per min., 250 volt, compound wound d-c. generator with interpoles direct connected to a 225-hp., 220-volt, 3-phase, 60-cycle, squirrel-cage induction motor.

The shaft of the generating unit is of two sections, one for generator and one for turbine, with forged half flanged sections bolted together upon installation. The turbine shaft has one guide bearing of the babbitted type mounted on the turbine crown plate. Lubrication is provided from a self contained gear pump driven from the main shaft. For emergency operation a float controlled rotary d-c. motor driven auxiliary oil pump is provided. The generator shaft has a Kingsbury thrust bearing with copper cooling coils and an upper and lower guide bearing of the babbitted type. The lubricating system for the generator shaft bearings consists of a gear pump, driven from the main shaft and located in the lower guide bearing oil pan.

The shaft of the pumping units is one piece forged steel with a Kingsbury combined upper guide and thrust bearing with copper cooling coils mounted on the upper spider designed to support the total weight and thrust; and a guide bearing between motor and pump, supported in a cast iron frame of heavy section bolted at the bottom to the upper head of the pump. Lubrication of all bearings on each unit is automatic from a motor driven gear pump, with a similar pump for spare for each unit.

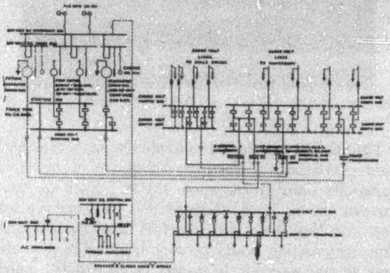

FIG. 8—SINGLE-LINE WIRING DIAGRAM OF ROCKY RIVER PLANT

*Station and Substation Equipment.* Under this heading there are five distinct groups:

a. 4600-volt indoor local distribution bus

b. 33,000-volt outdoor tie-in bus for Bulls Bridge station

c. 66,000-volt outdoor main station bus

d. 13,900-volt indoor bus for pumps

e. Station service busses.

A single line wiring diagram, Fig. 8, shows the general arrangements.

a. The 4600-volt bus is for distribution of power to the New Milford district. It was installed in the Rocky River power station so as to bring it under the supervision and control of the Rocky River power plant operators.

b. The 33,000-volt outdoor bus afforded the most economical arrangement for connecting the Bulls Bridge station (upstream from Rocky River about 8 mi.) to 66,000-volt main transmission system. At the same time this bus provides the means for later distribution of power, at a voltage higher than 4600 volts, to the more remote points of the New Milford district.

c. The 66,000-volt outdoor substation consists of a main and a transfer bus with switching equipment for the two 66,000-volt 3-phase lines to Waterbury, the 30,000-kv-a. transformer bank stepping down to 13,900 volts and the connection to the transformer banks stepping down to 33,000 volts and 4600 volts respectively. Space was left in the bus structure so that each of these two banks can be equipped with a separate circuit breaker. The 30,000-kv-a. main transformer bank has two oil circuit breakers, one of which acts as transfer breaker. Although the generating voltage is 13,900 volts the main station voltage is 66,000 volts. If it were not for the two pumping units there would be no bus and no switching equipment at 13,900 volts. As a matter of fact the second generating unit will be connected directly to its transformer bank as indicated on the wiring diagram in Fig. 8. The 66,000 volt side of the 30,000-kv-a. transformer bank is *Y*-connected and solidly grounded. The 13,900-volt windings are provided with 40, 50, and 60 per cent taps to obtain with an open-delta connection, approximately half voltage for starting the pumps.

d. The 13,900-volt indoor substation as mentioned above is for the sole purpose of supplying power to the pumping units. There are two busses, a full voltage running bus and a half voltage starting bus. The connections from the transformer bank to the busses are made with single conductor cables. The generator leads are connected to the running bus through a set of disconnecting switches with provision for a future oil circuit breaker. On the generator side of this tap is a non-automatic oil circuit breaker to disconnect the generator from the transformer bank before it is used to supply power to the pumps from the 66,000-volt bus. The two oil circuit breakers connecting each pumping unit to the starting and running busses are interlocked.

e. Station Service Busses. A 230-volt, 60-cycle, 3-phase bus supplies power primarily to the two motor-generator sets, the battery charging set, the sump pumps, air compressor, station lighting, etc. The main 250-volt, d-c. or exciter bus is, at present, divided into two sections, one for the generator, the other for the two pumps. The 250-volt d-c. emergency bus is supplied from one of the two motor-generator sets. The governor oil pump and the emergency turbine oil pump are normally connected to this bus; if power fails they are automatically switched over on to the 250-volt d-c. battery bus. All the control circuits and small d-c. motors in the plant are connected to the battery bus. The control battery was purchased large enough so that it can perform the double function of control battery and storage battery.

The fact that the plant is a peak load plant and that the pumps can be shut down for short periods without serious consequences and further that the generating unit is never operated at the same time as the pumps, made it possible to eliminate many duplications and reserve equipment which otherwise would have been necessary.

*Miscellaneous Equipment.* Inasmuch as part of the substructure of the plant is always below the water level in the Housatonic river, a sump was provided to collect any water which might possibly leak or seep into the basement. The sump is also connected to the draft tube of the generating unit and the intakes of the two pumps. All connections to the sump are controlled by hydraulically operated valves. Two 500-gal. per min. pumps are used for removing the water from the sump. An air compressor and pressure tank supply the air for the station, including the trash rack raking devices and the surge tank previously mentioned. Flow meters are installed to measure the water from the pumps and the water to the turbine. The water levels at the canal intake as well as in tail-race are recorded. Watthour meters record the output from the generator, the energy used by the pumps and for general station use.

The Rocky River development was designed and built by the U. G. I. Contracting Company of Philadelphia for the Connecticut Light and Power Company in close collaboration with the engineering staff of the Connecticut Light and Power Company.

### ADDITIONAL SUMMARY OF HYDRAULIC EQUIPMENT

*Main dam.* Length 952 ft., maximum distance from top to foundation 100 ft.

*Earth fill.* 367,800 cu. yd., 6 in. Wakefield core wall—31,000 sq. ft.

*Canal dike.* Length 2815 ft., earth fill, 332,000 cu. yd. 6 in. Wakefield core wall—52,000 sq. ft.

*Canal.* Length 3190 ft., excavation 708,200 cu. yd. Slope of sides generally 1 on 2 on cut side, 1 on 3 on dike side; Top elevation of dike 442 ft. Bottom 20 ft. wide at elev. 385 ft.

*Danbury dikes.* Earth fill, 59,000 cu. yd.

*Lanesville gap dike.* Earth fill, 18,000 cu. yd.

*North Lanesville spillway.* 175 cu. yd. concrete.

*South Lanesville spillway.* 742 cu. yd. concrete.

*Wood pipe line.* Approx. length 1007 ft., inside diameter 15 ft.; staves 4 in. by 6 in., tie rods ⅞ in. and 1 in. spaced 4 in. to 5¾ in.

*Steel penstock.* Approx. length 670 ft., inside diameter 13, 12, and 11 ft., thickness of steel plates ⅜ in. to ¾ in.

*Surge tank.* Johnson differential type. Shell diameter 28 ft., shell height 76 ft., riser diameter 9 ft., riser height 73 ft., orifices 4 ft. 4 in. diameter and 6 ft. 3 in. diameter.

*Dow pivot valves.* Diameter 54 in.—hydraulic cylinder operated.

*Sliding intake gate.* Self closing Broome gate 18 ft. 6 in. by 18 ft. 10 in. Opening 16 ft. diameter.

*Sliding suction intake gates.* Treadwell gate 6 ft. by 7 ft.

## Discussion

**P. M. Lincoln:** I should like to ask a question with regard to the last paper. There were certain figures which Mr. Amberg gave us on efficiencies reaching something over 100 per cent for certain conditions. I should like to ask whether or not those figures take account of evaporation. The matter of evaporation in a reservoir such as this where the water is stored over a period of years, must be a very important matter and must, of course, be considered carefully in the matter of calculating over-all efficiency. It strikes me the figures given are rather high, particularly if evaporation is to be considered.

**J. D. Justin:** I want to speak of Mr. Amberg's paper on the Rocky River Development. This development, due to its pumping feature, is entirely unique in America. However, in

Europe there have been some 35 or 40 plants that have been built along somewhat similar lines. One of these plants has a head of 540 ft., and there are two storage reservoirs. One of them is situated at the tail-water level and the other one forms the head-water with 540 ft. between them. The capacity of each reservoir is extremely small, only enough for daily operation. All this plant does at night when there isn't any peak load is to pump the water up in the reservoir at the top. Then over the peak-load period, the water comes down and goes through the turbines and produces energy on the peak of the load. The capacity of that plant is about 180,000 hp. There are 4 units, 45,000-hp. apiece. The pumps are somewhat larger than those at Rocky River and pump 640 cu. ft. of water a sec. each.

It seems to me rather remarkable that a plant like this, known as the Hengstey Plant in the Ruhr, Germany, would be economically justifiable in the heart of a coal region.

The capacity of the reservoir was less than 100,000,000 cu. ft.; in other words, about one-sixtieth of the capacity of the Rocky River reservoir.

I think there will be a good many more Rocky Rivers in America because there is an economic application for plants of this kind. In spite of all the advance in the steam plants, of mercury turbines and high-pressure units, there will still be some application for peak-load hydro plants where the cost of pumping for the high peak or the occasional peak would be a relatively small part of the alternate maintenance cost on the steam plant that would have to be provided to carry such peaks.

**C. L. Cate:** (communicated after adjournment) The Rocky River development goes further than the Swiss pumped-storage plants in that calculations have been based on using steam-generated power for pumping.

No data are given on the local storage at Bull's Bridge or Stevenson but with ordinary day-to-day pondage it is not clear how 50,000 kw. firm power is to be obtained from the three hydro plants as stated on the third page.

The author states that on the system of the Connecticut Light and Power Company there are no short-time peaks of any extent but that the system peak is the result of maximum 9-hr. day loads for which seasonal changes in load are responsible. This would indicate that during seasons of maximum load the load would be maintained at or near the peak for 9 hr. per day resulting in daily load factor of 37½ per cent on the hydro plants.

The 1914 hydrograph shows 6 months with an average run-off of about 0.3 cu. ft. per sec. per sq. mi. and 3 months with an average of 0.2 cu. ft. per sec. These figures would indicate maximum load factors of 20.4 per cent and 13.6 per cent respectively, at Bull's Bridge.

Corresponding figures for natural run-off at Stevenson would be 10.66 per cent and 7.1 per cent to which would be added water from the Rocky River plant operating at 37½ per cent load factor. This would increase the possible load factor at Stevenson by 13.6 per cent giving effective load factors of 24.26 per cent and 20.7 per cent which are both well below the 37½ per cent required. More water could be got to Stevenson by increasing the daily load factor at Rocky River but this would dissipate storage at a faster rate than allowed for in Mr. Amberg's calculations as given.

Fig. 5 shows on the lower curve representing present load a load factor of over 78 per cent for steam-generated power. If to this is added the steam required for pumping water the resulting load factor on the steam plant would apparently be over 90 per cent which seems somewhat high for a yearly load factor on steam equipment.

**E. J. Amberg:** In giving the figures for efficiencies and so forth, the very first thing we have done is to subtract from the run-off enough water to take care of evaporation. In other words, that 1,500,000,000 cu. ft. of water that we get in an average year from run-off is the net run-off after subtracting the run-off from 5 sq. mi. to take care of evaporation. We did that in order not to complicate the calculation of the studies afterward.

Now I want to add just a few words to what I said before in the application of such storage reservoirs. There are some advantages that can't be put down in dollars and cents. One advantage is that you have a generating unit which is instantly available in case of breakdown of another unit on the system. In a steam plant, to do that you have to carry additional turbine capacity and additional boilers on the line, and even then you can't always put on the machine quickly enough to save the shutdown.

There is another feature in the development. I showed 50 per cent of the load carried by the hydro plant. That is the basis we used for figuring and making sure that there was enough water under the extreme condition. In other words, if we had a load of 100,000 kw. we have 50,000 kw. in hydro units, we have 50,000 kw., let me call it, in active steam units and then we have 10,000 or 20,000 kw. in reserve steam units.

Now, in actual practise we would not operate 50,000 kw. of hydro capacity. We would operate first our steam units. In other words, we operate that so-called spare steam unit and keep our reserve in the hydro which of course would give us more leeway on that limited 24-hr. firm hydro capacity that we had. Instead of running the hydro capacity down to 50,000 kw. we would only run it down to 60,000 kw. (Fig. 5) which would probably take off 30 per cent of the energy that was in the shaded area and leave that much as an additional safeguard on the pumping scheme.

We have now on our system in Connecticut a load factor of 50 per cent which gives a fairly large base for the upper half of the load curve (Fig. 5). On account of the high system load factor we are limited in application to a 50-50 ratio between hydro and steam capacity. If the load factor on our system were only 35 per cent we could then with the same amount of primary hydro energy available develop more than 50,000 kw. in capacity. In other words we could obtain a ratio of say 60 to 40 as between hydro and steam or even better than that. From this it can be seen that systems with a lower annual load factor than we have could make a better use of such a pumped-storage development because they could install more hydro capacity and to that extent increase the value of the development over and above the value which it represents on the Connecticut Light and Power Company system.

Mr. Cate in his discussion points out that for the extreme condition of maximum system load and minimum flow of water in the river the Rocky River Plant will have to be operated beyond the 9-hr. period in order to release sufficient water for the Stevenson Plant to produce its full share of the load. This statement for the extreme condition is correct but I should not call it a dissipation of storage and it certainly is not dissipated faster than allowed for in our calculations. In studying load curves we also find that the maximum hour occurs only once a year and that even for the day of maximum hour the 9-hr. average is considerably less than the maximum hour. We further find that the average of the other days in the week which had the maximum peak is considerably below the maximum peak so that the matter is not as serious as it would appear when assuming that this maximum peak condition continues throughout a week or more. The answer to this particular problem is the duration load curve shown in Fig. 5 which indicates clearly that the high loads do not and cannot occur very frequently because the load drops off rapidly.

The distinction I wanted to make is between having 15-min. or half-hourly peaks scattered over many days or to have the same equivalent energy concentrated in a maximum week of the year as is the case on our system.

On account of the high loads being "bunched" in our case it is necessary to store the water from one season of the year to another.

Our calculations absolutely were figured to take care of the most extreme condition. This most extreme condition will happen only once in probably 50 years because it will require a coincidence of maximum output week and maximum peak load falling together; further it would require minimum river flow at the same time and it would further require that the reserve steam unit was out of commission. I have pointed out as one of the advantages of the hydro system the fact that under practical operating conditions the spare capacity would not be kept in the steam plant as assumed when making the study of this development but would be kept in the hydro plants and the spare steam unit would be actually used for daily operation. In this way the requirements on the hydro system would be very materially reduced.

Mr. Cate also questions the high load factor for the steam-generated power. In connection with this I simply want to call attention to the fact that this is the load factor of the power generated by steam but is not the station load factor because the reserve capacity is kept in the steam plant and if we compared the output of the steam plant based on 100 per cent use of its full installed capacity with the kilowatt-hours actually generated with the capacity actually required to carry the load we would obtain a station load factor which is considerably below that shown in the paper.

## THE APPLICATION OF RELAYS FOR THE PROTECTION OF POWER SYSTEM INTER-CONNECTIONS[1]

(L. N. Crichton and H. C. Graves, Jr.)

New Haven, Conn., May 9, 1928

**O. C. Traver:** The pilot wire scheme has been given a reasonably clean bill by Messrs. Crichton and Graves, although it is clear that the only important objection thereto is the cost of the pilot conductors. The exceedingly prompt action in case of internal faults and freedom from tripping on any external trouble is winning increasing favor in spite of this handicap.

For the longer transmission lines, carrier current may be a solution to the problem, as, by its use, we may secure a similar result without the need of the auxiliary wires connecting the two ends of the line, and I will try to give a crude mental picture of the principle of the carrier-current scheme as we are interested in it at Schenectady, and as it is being tried out by the Ohio Power Company at the present time. The plate supply of the oscillator is taken directly from the current transformer and accordingly oscillation can occur only on the positive half wave, and is transmitted half the time, that is, on each half cycle. At the receiving tube, the plate supply is again taken from the current-transformer secondary so that current can only flow through it each half cycle and then only if the grid potential permits. This grid is controlled by the carrier from the far end with the result that the plate current flows only in case the instantaneous directions of the main currents at the two ends of the line are alike, thus indicating a sound feeder. Under these conditions, the over-current relays are simply restrained from functioning.

Should a fault occur on the protected line and the instantaneous directions at the two ends, therefore, be in opposition, the receiving tube plate current would not flow, and the over-current relays would be free to trip the breaker. If this line should be down, short-circuited, or broken, so as to prevent the passage of the carrier, then the failure of the carrier to appear at the receiving end would leave the over-current relays free to operate and thereby give complete protection.

In other words, by simply matching the instantaneous direction of the currents at the two ends of the line, we can tell whether the current going in is also going out at the same time, under which condition we say it is all right, or whether it is flowing inward from both ends, which is all wrong, or whether by chance it is going in one end and the other end is passing nothing, in which case we can, and do, take out the end carrying any current worth considering. We can secure operation within ¼ sec. This quick action is of great importance as all operating engineers know. (For a full description, see "*A Carrier Current Pilot System of Transmission Line Protection*, by A. S. Fitzgerald, A. I. E. E. Quarterly Trans., Vol. 47, No. 1, Jan. 1928, p. 22.)

This paper indicates that many operating engineers hesitate about installing differential protection where many bushing-type current transformers must be connected in parallel in bus protection. Bushing transformers of the high ratio usually involved in such protection are generally as good as any.

I think there is no question of the more rapid action of balanced current protection as compared with impedance relays, so far as available equipment is concerned. Speed, again, is the important consideration, and balanced current relays have it. The impedance relay has a compensating advantage in that it can a little more simply care for the remaining single line.

The fault-detecting relay suggested by the authors involving two extra relays (over-current and undervoltage) does not seem as simple as one combining the two functions. Relays of the standard over-current type are available in which there is provided a voltage restraining action that simply changes the minimum operating current and leaves the time features as they were. This, of course, is in the nature of an impedance relay, but it is known by the descriptive name "Over-current-Undervoltage Relay." If, on a system, you need to care for a condition involving short circuits under light load conditions which are lower than the load currents at another time, this over-current-undervoltage relay will give the accustomed time characteristics but with a sliding current setting which is automatically adjusted by the system voltage.

In regard to the polyphase directional relay, I want to thank the authors for a very good defense of the practise which the General Electric Company has followed for some ten years back. We quite agree that the polyphase relay is a good one and hope they continue to make proper use of it.

I like the impedance-relay principle and believe more will be heard of it as conditions require, but the complication of Fig. 25 does not appear justified from any general point of view. Of the sixteen relay elements shown, the one ground relay can do from 90 to 95 per cent of the work. The table in Fig. 8, making its comparison on the basis of this unusual condition, is accordingly of very little value for the average system.

**L. N. Crichton:** Referring to Mr. Traver's discussion, the carrier-current relay protective scheme, which his company is interested in, is quite ingenious, and I am sure everyone is going to watch it with interest. It has a few disadvantages but so does every relay scheme, and I imagine it will be no harder, and perhaps easier to overcome those troubles than those of some other relay schemes.

The difficulty with bushing transformers for differential bus protection, mentioned in the paper, is something that has actually occurred on high-voltage transformers of a comparatively low ratio. There was quite a number of them in parallel, and it was found that if one of the transformers was dead, that is, the line was dead, the current from some of the other transformers would leak through it. Now, this was prevented in one case by putting auxiliary switches on the circuit breaker to cut out its transformer whenever the breaker was open. But this is bad because the switch may corrode or otherwise cause an open circuit and thus result in an unbalance which will cause improper operation.

There is not much doubt that any balanced relay will be a little faster than present impedance relays, but the difference in time will be small compared to the time required for the circuit breakers to open, that is, with present-day breakers. When making such comparisons it should be borne in mind that balanced schemes have their own troubles and objections.

Referring to the polyphase directional relay, there are not more than a half dozen systems in this country which demand its use. Most of the others can be served at least as well by the single-phase relay, maybe better.

All of us hope that there will not be many systems as complicated as that shown in Fig. 25 and Mr. Traver is correct in his statement that one of the relays shown will care for 90 to 95 per cent of the troubles. However, the remaining 10 or 5 per cent, or possibly less, must be cared for and the service is important enough to justify the extra relays. This installation is not the idea of one or two men but was chosen by a number of engineers intimately concerned with its success.

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[1] A. I. E. E. Quarterly Trans., Vol. 47, No. 1, Jan. 1928, p. 259.

## OSCILLOGRAPH RECORDING OF TRANSMISSION LINE DISTURBANCES[1]

(J. W. Legg)

New Haven, Conn., May 9, 1928

**M. A. Rusher:** I should like to ask whether the twin vibrator element requires two air gaps in series or a single gap of greater width than that used with the standard vibrator element? Are the sensitivity and the natural frequency of this element the same as that of the standard oscillograph vibrator element?

I should also like to ask whether, in putting 15 records on one film, complication of records will not be introduced which will make it impossible to distinguish one curve from another?

It may be of interest in this connection that about ten years ago the General Electric Company built a 15-element oscillograph. The record used was over 12 in. wide and one of the main reasons for not building more of that type of oscillograph was that the records were difficult to read due to different curves running into each other.

I was also interested in the discussion with regard to the wattmeter elements for measuring power. For a number of years we have been using a three-phase oscillographic wattmeter for transmission-line tests. This instrument records the average power rather than instantaneous power as Mr. Legg's wattmeter element does, but it gives a record which is very easily read, one from which the average power at any instant can be obtained without calculation other than applying a single calibration. When operated in connection with other oscillographs we have found that the records from this wattmeter were of very great value.

**Alexander Dovjikov:** Setting aside the field of application of the cathode-ray oscillograph we feel that the requirements for automatic recording of system faults are satisfied to the greatest extent by the oscillographic type of instrument described by Mr. Legg. One of the most important features which makes these oscillographs particularly appropriate for the study of system transients is the introduction of oscillographic wattmeter elements—elements which measure power and power oscillations directly. A knowledge of the variations in this quantity is particularly valuable because it is the difference in power quantities that produce acceleration or deceleration of the machine rotors and eventually results in pull-out.

The combination of the flexible automatic features of the oscillograph equipment and the phase-sequence network for initiating and measuring quantities supplies the operating engineer with *quantitative facts* on which to base an intelligent analysis of the system operation. Interpreting the data obtained by reading the oscillograms, the necessary changes and adjustments in the system may be made; subsequent records would prove whether these changes and adjustments resulted in improvement.

**J. W. Legg:** I have been asked a number of questions about some of the details of the vibrator and other things. As to the twin vibrator galvanometer, used in the 3-Element Power Osiso and in the 15-element oscillograph, it has an air gap of 0.055 in. instead of the usual air gap of 0.030 in., still its sensitivity is twice that of the standard oscillograph vibrator, and it responds very well to 1000 cycles and thus beyond the range required for recording power transients. The sensitivity is more than one hundred times that of the Hall Recorder so that the power consumed is quite small.

As to 15 records on one film, I believe I limited that and said that in some cases 15 could be used. If the limit of speed is 10 in. in 10 sec., then 15 records would be quite confusing, especially if a very fine lens system were not used. However, on some of the tests we drive a 24-ft. film through in 4 or 5 sec. on which the cycles are spread way out, and then when 15 records are used, one can find every bit of the detail in every record. I have not seen any films yet with nine records in which one could not pick out every bit of the detail.

In three-phase lines, the three voltages will be just out of phase with one another, and even though they all have the same zero, each wave is perfectly free, provided you have a reasonable speed of film. Of course, 10 in. in 10 sec. would cause considerable confusion with 15 records. I have one lantern slide that appears to show some interference; however, the original record is clear.

Now, there is the question of the instantaneous wattmeter versus the average-value wattmeter. Our company carried on tests for a number of years with the average-value wattmeter, both polyphase and single-phase. We have made a small average-power polyphase wattmeter which one can carry in the palm of one's hand. But for the most part, the instantaneous values of power are much preferable. All galvanometers occupy about the same space and are freely interchangeable in these oscillographs.

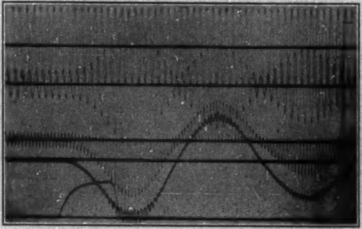

Fig. 1

In our 15-element oscillograph, the records are all in the same time-phase relation. This is not an improvised oscillograph. Previous ones were in reality a combination of several oscillographs, with one tier above the other, so that the light beams crossed at the cylindrical lens and reached the film half in one height and half in another, and thus gave a different time relation on the film. All fifteen of our records are in exact time-phase relationship, and easily controlled.

Many of the lantern slides shown when the paper was presented at New Haven were of oscillograms which were not available at the time the paper was written. The publication herewith of one showing a power surge recorded with a single-phase and polyphase instantaneous wattmeter should be more convincing than a lengthy written discussion.

The lower record is the short-circuit current of the d-c. end of a large motor-generator set. The one above this is of polyphase instantaneous watts, showing the surge of power from line to alternator, alternator to line, and so on. The record above that is single-phase instantaneous watts showing the changing power factor and kilovolt-amperes as well as giving a good idea of the surge of average power. The frequency here is twice that of the fundamental current or 120 cycles per sec. The record above shows instantaneous values of the a-c. in one line. The one above this, the top one, shows the instantaneous values of alternating potential in phase with the current when the power factor is unity. A comparison of the upper three waves will show the current lagging 90 deg. for zero power factor, lagging 180 deg. for minus unity power factor (when alternator is taking maximum power from line), and in phase with current when power factor is unity. However, the single-phase instantaneous watt curve tells a greater story than any other one record.

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[1] A. I. E. E. Quarterly Trans., Vol. 47, No. 1, Jan. 1928, p. 135.

# Symposium on Surge Voltage Investigations

## Surge Voltage Investigation on Transmission Lines

BY W. W. LEWIS*

Member, A. I. E. E.

***Synopsis.**—This paper and companion papers discuss the surge voltage investigation on six power systems in the lightning season of 1927.*

*Valuable data have been secured as to the nature and polarity, magnitude, wave-front and attenuation of surges, also the effect of overhead ground wires, choke coils, and lightning arresters.*

*Especially interesting is the attenuation formula $A = k\,e^s$, the form of which indicates a close connection between attenuation and corona loss.*

*Further investigations are being carried on in the present year to secure more complete and exact data on wave shape and attenuation, effect of ground wires, lightning arresters, and choke coils.*

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IN 1926 the General Electric Company conducted a surge voltage investigation on a limited scale in cooperation with the Pennsylvania Power & Light Company, New England Power Company, and Consumers Power Company. Thirty surge-voltage recorders in all were used. In 1927 the investigation was continued with a larger number of instruments on the systems mentioned, and some additional systems were included, namely, the Ohio Power Company, Alabama Power Company, and New York Power & Light Corporation. In all 130 instruments were in service.

This investigation yielded a vast amount of data, which has been sifted and analyzed, and it is the purpose of this and the companion papers[1] to present the more important data and the conclusions to be derived therefrom.

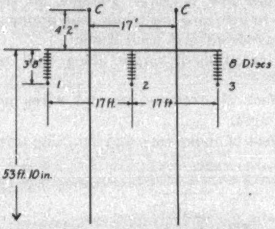

FIG. 1—DIAGRAM OF THE STANDARD TWO-POLE TOWER STRUCTURE USED ON THE LOCK 18—HATTIESBURG 110-KV. LINE OF THE ALABAMA POWER COMPANY

The wires marked *C* are the insulated communication circuits

The companion papers present in considerable detail a description of the system and the results of the investigation as far as the Pennsylvania Power & Light Company, New England Power Company, Ohio Power Company, and Consumers Power Company systems are concerned. The investigation on the Alabama Power Company and New York Power & Light Corporation's systems was not so extensive as on the other systems mentioned. Some data were obtained however, and these will be included in the present paper. A brief description of these two installations follows.

### ALABAMA POWER COMPANY INSTALLATION

The 110-kv. transmission line extending from Lock 18 power plant in Alabama to Hattiesburg, Mississippi, was under investigation. This is a single-circuit line on wooden pole *H* frame construction, Fig. 1. The design characteristics of the line are given in Table I.

Fig. 2 shows diagrammatically the arrangement of the conductors and the communication wires. The communication wires are transposed between stations as indicated. They are insulated by means of porcelain pin type insulators, nominally rated 23 kv. The communication circuits terminate at the various stations in insulating transformers, with their mid-point grounded. The pins of the insulators of the communication wires, as well as the crossarms supporting the line conductors, are grounded at each tower.

TABLE I
DESIGN CHARACTERISTICS OF LOCK 18—HATTIESBURG LINE OF ALABAMA POWER CO.

| | |
|---|---|
| Length | 225 mi. |
| Type of construction | Wood pole, *H*-frame (see Fig. 1) |
| Height of conductors at tower | 50 ft. |
| Configuration of conductors | Horizontal |
| Conductors | |
| Lock 18 to Meridian | 297,500 cir. mils ACSR |
| Meridian-Hattiesburg | 4/0 ACSR |
| Insulation | Suspension 8 disks OB-25622<br>Strain 9 disks OB-25622 |
| Transpositions | None |
| Communication wires | ½ in. steel and 1/0 ACSR (See Figs. 1 and 2) |
| Insulation of comm. wires | Pin type OB-12851 |
| Transpositions of comm. wire | See Fig. 2 |

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*General Electric Company, Schenectady, N. Y.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

Fig. 2 also shows the location of the surge-voltage recorders. Fig. 3 is a typical surge-voltage recorder installation.

### NEW YORK POWER & LIGHT CORPORATION INSTALLATION

A small portion of the 110-kv. and 33-kv. system of this company was under investigation. Fig. 4 shows this portion of the system and the location of the surge-voltage recorders. Table II gives the principal design characteristics. Fig. 5 shows a typical recorder installation.

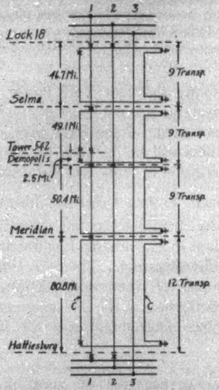


FIG. 2—ARRANGEMENT OF POWER CONDUCTORS AND COMMUNICATION WIRES ON LOCK 18—HATTIESBURG 110-KV. LINE OF THE ALABAMA POWER COMPANY

The power conductors are not transposed. The communication circuits are transposed frequently, the number of transpositions between stations being indicated on the diagram. To avoid confusion, the transpositions are not shown on the diagram. The location of the surge-voltage recorders is indicated by the symbol X.

TABLE II
DESIGN CHARACTERISTICS OF E-5 AND Q-95 LINES OF NEW YORK POWER & LIGHT CORP.

| | |
|---|---|
| **E-5 Line** | |
| Operating voltage | 110 kv. |
| Length | 4.08 mi. |
| Type of construction | Double circuit steel towers |
| Ground wire | 1 located at tip of tower |
| Insulation | Suspension 8 Locke 5800 disks<br>Strain 9 Locke 5800 disks |
| **Q-95 Line** | |
| Operating voltage | 33 kv. |
| Length | 24 mi. |
| Type of construction | Part steel tower, double circuit<br>Part wood pole |
| Ground wire | 2 on steel towers<br>3/8 in. steel |
| Insulation | Steel tower, 8 Locke 5800 suspension<br>9 Locke 5800 strain<br>Wood pole, 3 Locke 5800 |

### PURPOSE OF INVESTIGATION

The surge voltage investigation was conducted for the purpose of securing information on the following subjects:

FIG. 3—TYPICAL SURGE RECORDER INSTALLATION, ALABAMA POWER COMPANY

1. Nature and polarity of surges,
2. Magnitude of surge voltages on transmission lines due to lightning, switching, and arcing grounds,
3. Wave-front and wave-shape,
4. Attenuation of surges along the transmission line,
5. Effect of overhead ground wires in reducing surge voltages,
6. Effect of choke coils and lightning arresters.

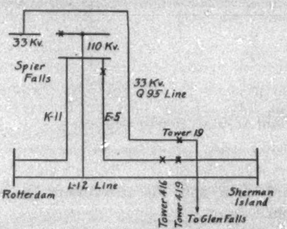


FIG. 4—PORTION OF NEW YORK POWER & LIGHT CORPORATION'S 110- AND 33-KV. SYSTEM

Surge-voltage recorder stations indicated by symbol X

Each of these items will be discussed in more or less detail.

*1. Nature and Polarity of Surges.*

Surges may be classified as unidirectional and oscillatory. The unidirectional surges may be positive or negative.

The oscillatory surges may be further classified as highly damped *H D,* medium damped *M D,* and slightly damped *S D.* A highly damped figure may be predominately positive or negative.

The *H D* figures are interpreted as being produced by a surge voltage which lasts for only a few polarity reversals, say less than five.

FIG. 5—TYPICAL SURGE RECORDER STATION, NEW YORK POWER & LIGHT CORPORATION

The *M D* figures are attributed to oscillations following flashovers between line conductor and ground. They appeared in this investigation only on the Consumers Power system, which was the only isolated neutral system in the investigation.

TABLE III
POLARITY OF LIGHTNING SURGES

| | Unidirectional | | | | Oscillatory* | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Positive | | Negative | | Positive | | Negative | | Equal | | |
| System | No. | Times Nor. | No. | Times Nor. | No. | Times Nor. | No. | Times Nor. | No. | Times Nor. | Remarks |
| Ohio Power Co. | 39 | 4.4 | 30 | 1.8 | | | | | | | 28 *HD*, max. 3.4<br>69 *SD*, max. 11.1 times normal |
| Pa. Pr. & Lt. Co. | 2 | 10.0 | 3 | 1.9 | 11 | 11.7 | 11 | 11.6 | 21 | 11.6 | |
| New England Power Co. | 8 | 1.7 | 11 | 3.0 | 21 | 7.4 | 39 | 10.0 | 25 | 6.9 | See note |
| Consumers Power Co. | 1 | 1.9 | 3 | 1.2 | 28 | 8.4 | 20 | 7.5 | 24 | 10.0 | |
| Alabama Power Co. | 1 | 1.3 | 3 | 2.2 | 4 | 2.6 | 4 | 6.8 | 15 | 4.5 | |
| New York Power & Light Corp. | 14 | 1.8 | 10 | 1.7 | 13 | 2.3 | 15 | 6.9 | 19 | 7.3 | All surges |
| Weighted total | 65 | 234 | 60 | 120 | 77 | 559 | 89 | 807 | 104 | 864 | |
| Average | | 3.6 | | 2.0 | | 7.25 | | 9.1 | | 8.3 | |
| Note: If surges are classed as to polarity at place where magnitude of surge was highest, following will result: | | | | | | | | | | | |
| New England Power Co. | 18 | 2.4 | 30 | 10.0 | 11 | 7.6 | 21 | 8.4 | 24 | 6.9 | |

*Classified as to whether surge is predominantly positive or negative, or with positive and negative equal.

The *S D* figures are of uncertain origin. They appear to be formed from a continuous application of a-c. potential for a duration of several seconds. They are thought to be connected with a particular potentiometer arrangement, as they did not appear when simultaneous records were taken with other potentiometer arrangements.

Examples of figures produced by the various classes of surges are given in Fig. 6 of this paper, and examples of *H D* and *S D* figures are also given in Lee and Foust's paper.[3]

Table III gives a summary of the lightning surges on the various systems classified as to polarity. All surges given as unidirectional were of the same polarity throughout at all stations where they were measured. Surge voltages given as oscillatory registered with both positive and negative polarity values at one or more stations, but many of these registered as unidirectional on some recorders. The generally low magnitude of the unidirectional surges shown by the table must be interpreted with this explanation in view. Unidirectional surges of high magnitude were obtained at some stations, but if the surge showed an oscillatory character at any other station, it was classed as oscillatory.

In the case of the New England Power Company a second classification is given in the table, in which the polarity is taken at the place where the magnitude of the surge was the highest. Classified in this manner the results appear somewhat different from the first classification.

The second classification is probably as reasonable as the first one. It is impossible in this study to separate the lightning surge from the switching surge which follows in case the line trips-out.

### 2. *Magnitude of Surge Voltages on Transmission Lines due to Lightning, Switching, and Arcing Grounds.*

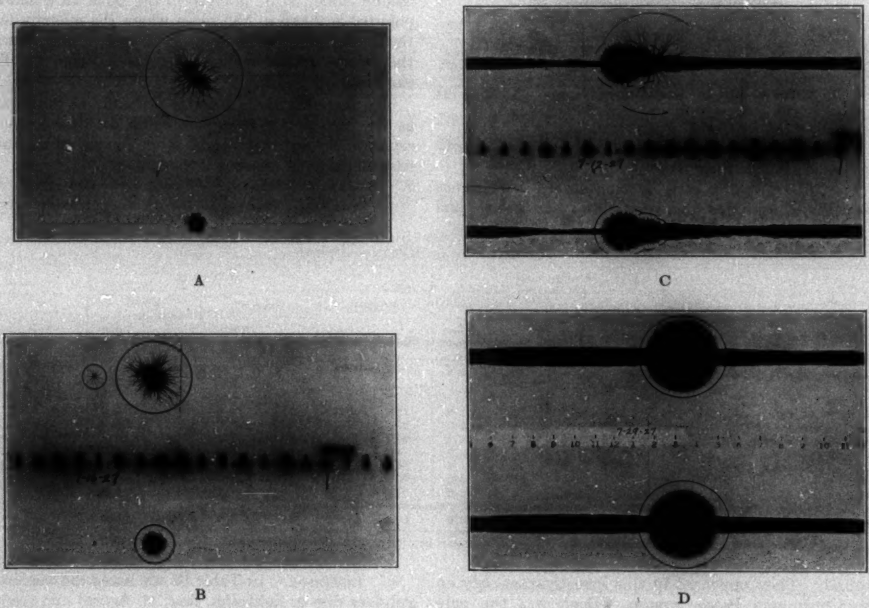
*a. Lightning.* In Table IV are listed the maximum voltages due to lightning, first, all figures and second, *H D* figures only. In this table are also listed the number of disks, type, and impulse flashover of the line insulators as determined in laboratory tests.[4]

It will be noted that the maximum voltage recorded in no case exceeds the impulse flashover values given, but is in most cases comparable in value or somewhat less. This would indicate that the impulse values given are fair values to use in estimating the lightning

TABLE IV
MAXIMUM VOLTAGE DUE TO LIGHTNING

| | Max. voltage | | Line insulation | | | Ht. of line | |
|---|---|---|---|---|---|---|---|
| | All figures | *HD* figures | Disks | Type | Impulse flashover kv. | At tower | Average ht. top cond. |
| Ohio Power Co | 1200 | 475 | 10–11–12 | OB–25622 | 1180–1400 | 60–73–86 | 70 |
| Pa. Pr. & Lt. Co | 2100 | 1800 | 14–16 | Locke 7500 | 1900–2140 | 66 | 50 |
| New England Power Co | 900 | 900 | 8–9 | OB–25620 | 1020–1120 | 49 | 40 |
| Consumers Power Co | 1140 + | 850 | 9 K–11<br>10 H–8 | OB–25622 | 1080–1180 | 45–58–70<br>40–46–52 | 60 |
| Alabama Power Co | 610 | 610 | 8–9 | OB–25622 | 970–1080 | 50 | 40 |
| New York Pr. & Lt. Corp | 660 | 620 | 8–9 | Locke 5800 | 1150–1270 | 46–56–66 | 50 |

| | Kv. per ft. of height | Kv. per ft. required to flash over insulators | Ratio kv. meas. to flash over kv. per cent | Normal voltage crest kv. to neutral | Maximum voltage no. times normal all figures |
|---|---|---|---|---|---|
| Ohio Power Co | 17 | 20 | 85 | 108 | 10.2 |
| Pa. Pr. & Lt. Co | 42 | 43 | 98 | 180 | 11.7 |
| New England Power Co | 23 | 28 | 82 | 90 | 10. |
| Consumers Power Co | 19 | 20 | 95 | 114 | 10. |
| Alabama Pr. Co | 15 | 27 | 55 | 90 | 6.8 |
| New York Pr. & Lt. Corp | 13 | 25 | 52 | 90 | 7.3 |



A C B D

Fig. 6—Lichtenberg Figures Illustrating Various Types of Surges

a. Negative surge
b. Highly damped surge
c. Medium damped surge
d. Slightly damped surge

flashover of transmission lines, and would further indicate that the maximum voltage induced on a line is limited by the insulator flashover.

In this table are also given the height of the lines at the tower and an estimated average height of the top conductor, also the kv. per ft. of height based on the maximum voltage for all classes of figures. The kv. per ft. of height required for flashover is given, based on the longest string listed. It will be noted in the last column of the table that voltages have been recorded from 52 to 98 per cent of the flashover value.

In most cases it is probable that the recorders were not located at the point of highest voltage. Also, it is possible that flashovers occur at much lower values than given in the table, which are based on a certain wave of very steep front. In practise the waves may be considerably less steep and otherwise different in shape.

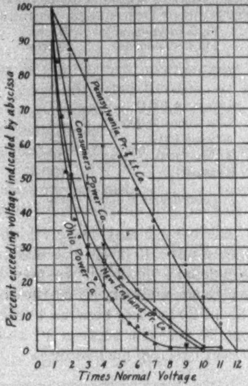


Fig. 7—Magnitude of Surge Voltages Due to Lightning on the Various Power Systems

Fig. 7 shows curves of surge voltages due to lightning for the various systems. In these curves the abcissas represent times normal crest to neutral volts, and the ordinates per cent of the total number exceeding the value indicated by the abcissas. All surges, *H D*, *M D*, and *S D*, have been grouped in these curves.

TABLE V
MAXIMUM VOLTAGE DUE TO SWITCHING

| System | Normal voltage crest kv. to neutral | Energizing times normal kv. | Deenergizing times normal kv. | Both times normal kv. |
|---|---|---|---|---|
| Ohio Power Co. | 108 | 4.2 | 5.2 | |
| Pa. Pr. & Lt. Co. | 180 | 4.0* | Less | |
| N. E. Pr. Co. | 90 | .. | .. | 4.0 |
| Cons. Pr. Co. | 114 | 3.0 | 3.6 | |
| Alabama Pr. Co. | 90 | 1.5 | 2.6 | |
| New York Pr. & Lt. Corp. | 90 | Less | 3.4 | |
| Average | | 3.2 | 3.7 | |

*On this system all switching was done on the low tension side.

It will be noted that the curves have the same general shape and that the majority of surges are of low value, *i. e.,* less than five times normal.

*b. Switching.* Table V gives the maximum voltages due to switching classified as to energizing and deenergizing lines.

It will be noted that deenergizing is slightly more severe than energizing.

Switching load on and off gives a very mild overvoltage disturbance, for example, 1.2 times normal on the Ohio Power Company's system.

The conclusions as to the relative severity of the various types of switching agree with conclusions arrived at previously with the oscillograph,[5] although the magnitudes recorded by the surge-voltage recorder are much greater than by the oscillograph.

In Fig. 8 are shown curves of switching surges for three systems, the abscissas representing the number of times normal and the ordinates representing percentage of all surges exceeding the given number of times normal shown on the abcissas.

It will be noted from these curves that the majority of all switching surges were less than three times normal.

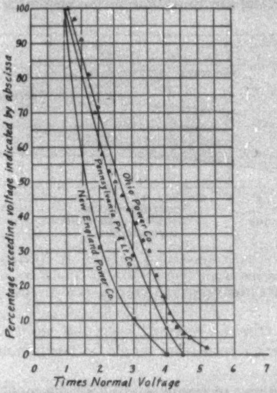


Fig. 8—Magnitude of Switching Surges on Various Systems

In these surges *H D* figures predominated. They were very general throughout a system, that is, they appeared at all the recorder stations and at practically the same value.

*c. Arcing Grounds.* It is not possible from this investigation to separate lightning surges from the arcing ground or switching surges which follow in many cases. The initial surge caused by lightning and the subsequent surges due to arcing grounds or switching are shown as one surge by the recorder.

The Consumers Power Company is the only one of the systems operating with an isolated neutral, and therefore the only one subject to overvoltage due to arcing grounds. It is possible that the *M D* figures found only on this system were caused by arcing grounds. Pure *M D* figures were found of a magnitude of 7.7 times normal. Such *M D* figures recorded on practically all instruments on the system and in some cases were coincident with switch trip-outs due to the operation of ground relays. In other cases the *M D* figures appeared coincidentally with system disturbances caused by arcing from the line wire to a tree. This incident accounted for five surges ranging from 2.5 to 3.6 normal times. Theoretically the maximum voltage that can be obtained from arcing grounds is about six times normal.[6]

*d. General.* From the data given it may be concluded that a transmission line insulated for about six times normal voltage, will be fairly safe from flashover due to switching or arcing grounds. The average system is insulated for this voltage or better.[6] The average system is also insulated for impulse voltages of 10 to 14 times normal.[4]

Since only a fraction of the voltages recorded reach the extreme value of 10 to 14 times normal on impulse (Fig. 7) and six times normal on switching or arcing grounds (Fig. 8), it would seem that most of the lines with average insulation should be fairly immune from flashover.

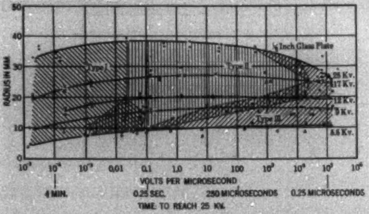


FIG. 9—CHART SHOWING VARIATION OF POSITIVE LICHTENBERG FIGURES WITH CREST VOLTAGE AND RATE OF VOLTAGE RISE, AND CLASSIFYING THE FIGURES INTO TYPES

That many of the lines are not so immune indicates that our data on the line insulation may not be exact, or our data as to voltage magnitude not complete. Then again, we know very little about the behavior of direct strokes.

### 3. *Wave-Front and Wave-Shape.*

Up to the present time we have not been able to obtain any data on the shape of the waves encountered on transmission lines. Some data as to the front of the wave have been obtained by inspection of Lichtenberg figures. The method is as follows: The figure is examined as to type and magnitude. This locates the surge somewhere within wide limits by means of the chart, Fig. 9, reproduced from Mr. K. B. McEachron's A. I. E. E. paper.[2] If the surge appears at another station on the system, it may appear with a different magnitude and slope and perhaps be of a different type. Thus, it is possible by inspection of figures of the same surge appearing at two or more stations, to establish the time of the front within wide limits.

Mr. K. B. McEachron has examined the records of about 150 figures in this manner. The results of this study are shown in Table VI. It will be noted from this table that only one figure definitely indicated a front less than one microsecond, although some of those classed as less than 10 microseconds may also be less than 1.0 microsecond, likewise for those classed as less than 100 and 100,000 microseconds. Those classed as at least 1.0 microsecond may be anything over 1.0 microsecond, even up to 10 or 100 microseconds.

TABLE VI
TIME OF FRONT OF WAVE AS INDICATED BY INSPECTION OF LICHTENBERG FIGURES

| Time to reach crest in microseconds | No. of figures |
|---|---|
| Less than 1.0 | 1 |
| Less than 10.0 | 1 |
| Less than 100.0 | 11 |
| Less than 100,000 | 44 |
| At least 100.0 | 48 |
| At least 10.0 | 16 |
| At least 1.0 | 33 |
| Total figures | 154 |

From this indefinite grouping, we may make the following very rough summary as to the duration of wave-front: about 20 per cent between 1 and 10 microseconds, about 20 per cent between 10 and 100 and about 60 per cent over 100 microseconds.

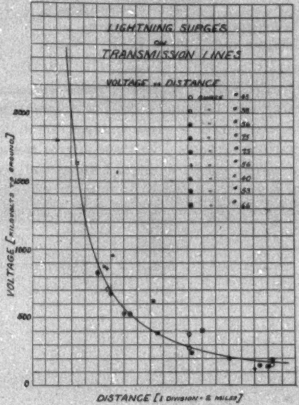


FIG. 10—CURVE SHOWING VARIATION OF VOLTAGE WITH DISTANCE FOR VARIOUS SURGES

Surges 38 and 40 are on Pennsylvania Power & Light Company's system, all others on New England Power system.

There is some indication from this study, that the waves of highest magnitude are also the steepest.

### 4. *Attenuation of the Surges along the Transmission Line.*

C. M. Foust and F. B. Menger have plotted a number of surges (Fig. 10) which appeared at more than one station, with distance from an assumed origin as abscissas and voltage as ordinates. They then drew an average curve and determined equations for the variation of voltage with distance, and the rate of change of voltage with distance or attenuation. These equations are as follows:

$$e = \frac{e_0}{k\, l\, e_0 + 1} \qquad (1)$$

$$A = -\, k\, e^2 \qquad (2)$$

in which

$e_0$ = the initial voltage at the point where the surge originated

$k$ = a proportionality factor which is found empirically

$l$ = the distance in miles from the origin of the surge

$e$ = voltage at any distance $l$

$A$ = the attenuation in kilovolts per mile.

The factor $k$ for all the surges investigated has been found to be about 0.00016.

These equations are used as in the following examples:

1. Assume the initial potential to be 2000 kv. Then at a distance 10 mi. from the origin:

$$e = \frac{2000}{(0.00016 \times 10 \times 2000) + 1} = 477 \text{ kv.}$$

The attenuation at the point of origin of the surge is

$$A = -\,0.00016 \times 2000^2$$
$$= -\,640 \text{ kv. per mi.}$$

2. If the initial surge was only 1000 kv. in magnitude, then the attenuation would be

$$A = -\,0.00016 \times 1000^2$$
$$= -\,160 \text{ kv. per mi.}$$

As a limiting case for any line, the flashover value of the line insulation may be taken as the initial voltage.

Equations (1) and (2) have a great deal of significance They state that the voltage varies inversely as the distance and that the attenuation varies as the square of the voltage. Since attenuation depends on resistance loss in the conductor and corona loss, and since it is known that resistance loss accounts for only a small amount of attenuation, the greater part of it must be due to corona loss. Corona loss varies as the square of the voltage, so that the attenuation, Equation (2), seems to tie in with the corona loss. The factor $k$ probably varies with the size and spacing of the conductors on the transmission line, but for the various lines in this study the average of 0.00016 gave results which agree fairly well with the test data.

It seems likely that the particular units chosen for distance and potential have more effect on $k$ than anything else. In our case we have used miles and kilovolts. If other units were used, such as absolute units, a different value for $k$ would result. More data and more study may serve to refine this factor somewhat. Equations (1) and (2) are plotted in curve form in Fig. 11, assuming initial voltage $e_0$ = 1000 kv.

In this figure attenuation has been plotted for convenience as positive, although it will be noted from Equation (2) that it is a negative function.

The following example served as a useful check on the formulas: Surge No. 75 on the New England Power system gave readings at several stations. Assuming the voltage at the origin to be 1000 kv. (the estimated flashover value of the line insulators) the distance to the origin from one of the stations was computed and found to be 25 mi. Visual inspection indicated a flashover at 21.5 mi. from the station.

### 5. *Effect of Overhead Ground Wires in Reducing Surge Voltages.*

The ground wire data are rather inconclusive, mainly because of a lack of exact comparison between lines with and without ground wires, and also because of the effect of reflections. The surge-voltage recorder measures the maximum voltage regardless of whether the maximum is the initial voltage or the reflected voltage. Nevertheless the data have given a few indications of the effect of the ground wire.

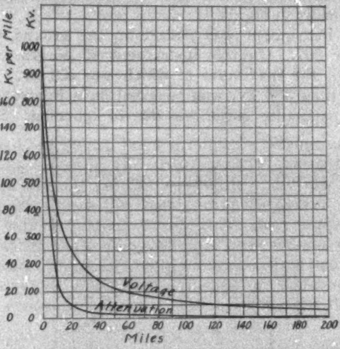


Fig. 11—Variation of Voltage with Distance and Rate of Decrease of Voltage with Distance, from Equations (1) and (2). Initial Voltage 1000 Kv.

*a. Ohio Power Company's System.* Approximately 50 surges were measured simultaneously on top, middle, and bottom conductors of the vertically arranged circuit. This line is a double circuit line with one overhead ground wire above and midway between the two circuits. In Table VII is given the theoretical potential of the three conductors without ground wire, expressed in per cent, on the assumption that the bottom conductor is 100 per cent and that the other conductors have potentials proportional to their heights above ground. Then there is given the theoretical potential with ground wire, still assuming that the bottom conductor is 100 per cent and using the protective ratios given in Reference 4, *i. e.*, 0.42, 0.52, and 0.62, for top, bottom, and lower conductors respectively. Finally is given the average of the surge-voltage recorder readings expressed in per cent, with the bottom conductor as 100 per cent.

The order of the actual protection agrees with the theoretical, but is not so favorable as the theoretical based on ideal conditions. The results are illustrated graphically in Fig. 12.

TABLE VII
EFFECT OF OVERHEAD GROUND WIRE
OHIO POWER CO.

| Conductor | Approx. height at tower—ft. | Theoretical potential without ground wire per cent | Theoretical potential with ground wire* per cent | Measured potential with ground wire. Average of readings per cent |
|---|---|---|---|---|
| Top........ | 85 | 143 | 68 | 89 |
| Middle..... | 72 | 121 | 84 | 98 |
| Bottom.... | 59 | 100 | 100 | 100 |

*Calculated by means of tables in Reference 4.

An instrument was placed on the ground wire at Tower 297. On this instrument 65 surges were recorded, the maximum of which was 8.2 kv. At the same time 380 kv. was recorded on a line conductor. This particular surge was due to lightning. Seventy per cent of all the surges were over 3 kv. Many of the surges were tied up with switching on the transmission lines.

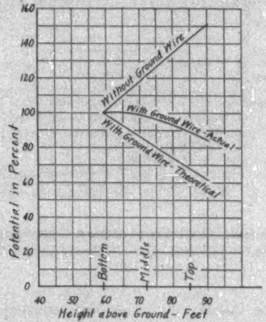


FIG. 12—GROUND WIRE PROTECTION, OHIO POWER COMPANY'S SYSTEM

*b. Pennsylvania Power & Light Company's System.* This 65-mi. line is equipped with 20 mi. of ground wire at the Wallenpaupack end and four mi. at the Siegfried end.

There were three periods of operation in 1927, (1) without ground wire, that is up to May 24, (2) period of installing ground wire, line not energized, May 24 to July 24, and (3) with ground wire, after July 24.

Any readings taken on the portion of the line not covered by ground wire are subject to reflection at the junction between the covered and not covered portions. Likewise the portions under the ground wire are subject to reflection at the terminals. All we can look for, therefore, is a tendency or trend.

For the period after the ground wire was installed a curve was drawn showing the highest values of surges recorded at stations along the line, and the average values of the surges recorded at the stations. The average of the highest values and the average of the averages were then taken for the unprotected portion of the line and for the protected portions. Table VIII shows the averages.

TABLE VIII
EFFECT OF OVERHEAD GROUND WIRE
PENNSYLVANIA POWER & LIGHT CO.

| | Unprotected | | Protected by ground wire | | | |
|---|---|---|---|---|---|---|
| | | | Wallenpaupack end | | Siegfried end | |
| | Times normal | Per cent | Times normal | Per cent | Times normal | Per cent |
| Average of highest...... | 7.1 | 100 | 5.6 | 80 | 7.4 | 104 |
| Average of all values....... | 4.4 | 100 | 3.6 | 82 | 4.0 | 91 |
| Theoretical (two ground wires)....... | | 100 | | 35* | | |

*From reference 4.

*c. New England Power System.* On this system the transmission line under test consisted of two circuits horizontally arranged. The conductors may be designated 1, 2, 3, 4, 5, 6. There was one ground wire above and between conductors 2 and 3. Instruments were installed on all six conductors at two places, Griswoldville and Barre. The readings on these instruments did not necessarily indicate the potential due to the conductor position at that point, because the conductors were frequently transposed. The fairest attempt to evaluate the effect of the ground wire was to select those surges which had their highest values at one of the stations, and therefore presumably originated near that station. For this purpose five surges which had their highest value at Barre were selected. The readings are given in Table IX.

TABLE IX
EFFECT OF OVERHEAD GROUND WIRE—NEW ENGLAND POWER CO. SURGE VOLTAGES HAVING THEIR HIGHEST VALUE AT BARRE

| Surge no. | Conductor position Number of times normal | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 59............ | 5.2 | 3.9 | 3.3 | 2.2 | 4.2 | 4.2 |
| 66............ | 9.0 | 3.9 | 6.5 | 3.8 | 6.0 | 6.1 |
| 88............ | 3.1 | 2.5 | 4.0 | 2.8 | 3.5 | 5.3 |
| 113........... | 2.8 | 2.7 | 3.2 | 2.8 | 2.7 | 8.3 |
| 114........... | 4.0 | 2.8 | 3.9 | 5.0 | 5.5 | 8.3 |
| Average....... | 4.8 | 3.1 | 4.2 | 3.3 | 4.4 | 6.4 |
| Per cent....... | 75 | 48 | 66 | 52 | 69 | 100 |
| Theoretical per cent*........ | 74 | 64 | 64 | 74 | 89 | 100 |

*From Reference 4.
Ground wire above and between conductors 2 and 3.

It will be noted that these readings are not entirely consistent, sometimes one conductor being highest and sometimes another. The averages of the five surges are plotted in Fig. 13. The averages of the readings expressed in per cent agree fairly well with the theoretical protection to be expected.[4] Fig. 13 also shows the number of flashovers that took place in 1927 on the various conductors at all parts of the line, as indicated by a visual inspection. A somewhat irregular flashover curve is to be expected, because under the worst conditions the ground wire would only reduce the potential on the most favored conductors to about 2000 kv. and the other conductors would have higher potentials. This potential is about twice the flashover value of the insulators, and it is a matter of chance which conductor spills over.

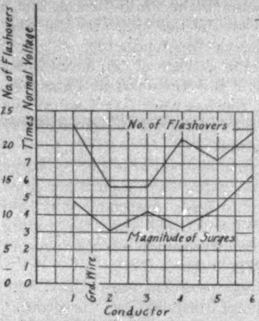


FIG. 13—POTENTIAL MEASURED ON VARIOUS CONDUCTORS AND FLASHOVERS OBSERVED, NEW ENGLAND POWER COMPANY

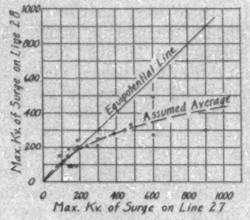


FIG. 14—GROUND WIRE PROTECTION, NEW ENGLAND POWER COMPANY, AS INDICATED BY READINGS AT GRISWOLDVILLE

Another effort to evaluate the effect of the ground wire has been made by plotting the highest crest value of lightning surges on line 27 (without ground wire) as abscissas and the highest values on line 28 (with ground wire) as ordinates. A reference line at 45 deg. is drawn to assist in interpreting the results. Fig. 14 shows the points plotted from the readings taken at Griswoldville and Fig. 15 at Barre. An average curve drawn through these points assumes a general drooping shape indicating the beneficial effect of the ground wire. This is more apparent on the readings at Griswoldville (Fig. 14) than those at Barre (Fig. 15).

*d. Consumers Power Company.* On this system there were two lines under investigation, the *H*-8 and *K*-11 lines between Saginaw River and Flint. These lines were on separate structures and in some cases as much as 10 mi. apart, being in multiple, however, at the two ends. During the entire season the *H*-8 line operated without ground wire while the *K*-11 had a ground wire during the latter part of the season.

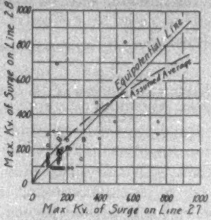


FIG. 15—GROUND WIRE PROTECTION, NEW ENGLAND POWER COMPANY, AS INDICATED BY READINGS AT BARRE

For various reasons it is difficult to compare the performance of the *H*-8 and *K*-11 lines. Some of the reasons are: difference in tower height and configuration of conductors, difference in insulation, difference in size of conductor, also the fact that lines are tied together at ends and to other lines on which the trouble may originate. It is also difficult to compare the performance of the *K*-11 line before the ground wire was installed and after, because comparatively few high voltage surges were recorded, and very few of them before the ground wire was installed. About the only thing we can do is to compare the maximum potential on the two lines before and after the ground wire was installed, and also to compare the maximum obtained on the three conductors of the *K*-11 line before and after the installation of the ground wire. This is done in Table X. The results show a slightly lower maximum potential on the *K*-11 line after the ground wire was installed,

TABLE X
CONSUMERS POWER CO. HIGHEST POTENTIALS OBTAINED BEFORE AND AFTER GROUND WIRE WAS INSTALLED ON *K*-11 LINE

| Line | Before ground wire installed times normal | After ground wire installed times normal |
|---|---|---|
| *H*-8 | 9 | 10 |
| *K*-11 | 9 | 8 |
| *K*-11 Top | 8 | 6 |
| Middle | 9 | 8 |
| Bottom | 7.7 | 5.9 |

while at the same time the H-8 line, which had no ground wire, showed a slightly higher potential.

On the ground wire itself a number of surges was measured at tower 318 and midway between towers 318 and 319. The results of these readings are shown in Table XI.

In only one case was any potential indicated at the tower. The potential at the mid-span varied from 2 to something over 35 kv. All these potentials are small compared with the potential on the line conductor, and indicate that the ground wire is maintained near enough to ground potential to be effective in performing its protective function..

TABLE XI
CONSUMERS POWER CO.
POTENTIAL MEASURED ON GROUND WIRE
Kv. Crest

| Surge no. | At mid-span towers 318 and 319 | At tower 318 | On conductor at tower 318 |
|---|---|---|---|
| 116 | 35 + | 28 | 206 |
| 166 | 24 | 0 | 456 |
| 146 | 6 | 0 | 410 |
| 148.1 | 5.5 | 0 | .. |
| 87 | 3.7 | 0 | 850 |
| 94 | 2. | 0 | 205 |

*e. Alabama Power Company.* As described previously, this is a single circuit line with conductors horizontally arranged and two lightly insulated overhead communication wires, which are connected to ground through transformers at the stations. Fig. 16 shows a comparison between the potential on the middle conductor as abcissas and the potential on one of the outside conductors as ordinates. A 45-deg. line is plotted for reference. It will be noted that there are more points above the 45-deg. line than below, indicating that the outside phase is subject more to high voltage than the middle conductor.

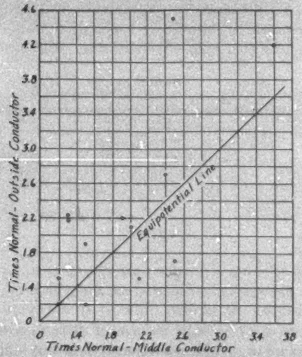


FIG. 16—COMPARISON BETWEEN POTENTIAL ON MIDDLE AND OUTSIDE CONDUCTORS, ALABAMA POWER COMPANY

On the insulated communication wire itself surges were recorded varying from 120 to 170 kv. As would be expected, these figures indicate that this wire is not kept as near ground potential as a wire which is connected to ground at each tower. Such an insulated wire should therefore not offer as effective protection as a wire more thoroughly connected to ground.

### 6. *Effect of Choke Coils and Lightning Arresters.*

At both ends of the Philo-Canton line, instruments were placed on the bus side and the line side of the choke coils on the top conductor.

Based on the average of ten simultaneous readings, the line side of the choke coil at Philo was 15 per cent higher than the bus side. At Canton the average of 12 readings showed the line side to be six per cent higher than the bus side.

It is not possible to say whether the surges originated on the Philo-Canton line or on other lines tied to the Philo or Canton bus. Assuming that they originated on the Philo-Canton line then the averages obtained indicate a small reflection of the incoming surges at the choke coils.

Surge-voltage recorders were placed across about 12 ohms resistance, installed in the ground or neutral end of the four-stack oxide film arresters at Canton, Newcomerstown, Philo, and Turner. Only two instruments gave records, those at Newcomerstown and Turner. Both switching and lightning surges apparently cause discharges, although the majority were tied in with lightning.

The current measurements varied from 150 to 2620 amperes. One reading was 1260 amperes, one 2620, and the balance were below 450 amperes.

On this system there were 97 highly damped lightning surges recorded. Of these only four were above two times normal. There were also 69 lightning surges classified as slightly damped, of which 31 were over three times normal and 18 over four times normal. Probably about three times normal is required between line and ground before the arrester gaps arc over, on account of the gap setting and the division of voltage between gap and arrester stack. The fact that only about one-fifth of all the surges recorded as due to lightning were over three times normal, and that not all of these were highest in the vicinity of the arresters, may account for the comparatively few readings of arrester discharge taken during the summer.

## CONCLUSIONS

Some surge voltages due to lightning are unidirectional and some are oscillatory. Of the unidirectional surge voltages, some are positive and some are negative. Of the oscillatory surge voltages, some have positive characteristics predominating and some have negative.

While there may be a trend in some systems toward certain polarity characteristics, the surge voltages recorded on these systems are not exclusively of these characteristics. It is certain that all unidirectional surge voltages of highest crest value are not of negative polarity, for several of positive polarity have been recorded. High-voltage surges of negative characteristics are in the majority however.

The oscillatory surges have been classified as highly damped *H D*, medium damped *M D*, and slightly damped *S D*. The *H D* figures are accepted without question. The *S D* figures are of doubtful origin.

The *M D* figures appeared only on one system, which operates with an isolated neutral. These figures reached a magnitude of 7.7 times normal and are thought to be associated with arcing grounds.

Surge voltages of the following upper magnitudes have been measured on the various systems:

Due to lightning, 7 to 12 times normal.
Due to switching, 2 to 5 times normal.

These values check those of previous investigations.[7]

It has been fairly well established that the voltage is limited by the flashover strength of the line insulators which on the average system is from 10 to 14 times normal[4] (normal equals crest value of line to neutral voltage).

Very little is known yet about the shapes of the waves encountered in lightning and other line disturbances. The wave-front varies through wide limits. Of 154 surges examined, about one-fifth had fronts between one and ten microseconds, about one-fifth between 10 and 100 microseconds, and about three-fifths over 100 microseconds.

An empirical formula has been derived for attenuation. This is of the form $A = k\,e^2$. That is, the attenuation is faster the higher the voltage. The form of this equation is similar to that for corona loss, $p = c\,e^2$, and indicates that the attenuation is due mainly to corona loss.

The study has shown the benefit due to overhead ground wire in some cases to be very small and in other cases to be almost up to the theoretical value. A conclusive study is very difficult to make, as it is almost impossible to obtain two lines of identical arrangement, in identical territory, subject to the same lightning conditions, and one with and one without ground wire.

The data as to the effect of choke coils and lightning arresters are meager and more information must be obtained along this line.

The data showed from 6 to 15 per cent difference of potential across the standard line choke coils.

Lightning arresters showed discharge currents varying from 150 to 2600 amperes.

In the present year efforts are to be made to obtain more complete and exact data on a few systems. A special effort will be made to obtain data on wave-shape, attenuation, effect of ground wires, and effect of lightning arresters and choke coils.

### ACKNOWLEDGMENTS

The laboratory work in connection with this investigation was under the direction of Mr. E. S. Lee.

Acknowledgment is due C. M. Foust, A. L. Price, F. B. Menger, J. A. Tiedeman, R. F. McAtee, and others of the General Engineering Laboratory and J. B. McClure of the Central Station Engineering Department of the General Electric Company for their painstaking work in handling, analyzing, and correlating the large mass of data accumulated in this investigation. The hearty cooperation of the various power companies is also acknowledged.

## References

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2. *Measurement of Transients by Lichtenberg Figures*, K. B. McEachron, A. I. E. E. TRANS., Vol. XLV, 1926, p. 712.

3. *Measurement of Surge Voltage on Transmission Lines due to Lightning*, E. S. Lee and C. M. Foust, A. I. E. E. TRANS., Vol. XLVI, 1927, p. 339.

4. *Relation between Transmission Line Insulation and Transformer Insulation*, W. W. Lewis, New Haven Meeting of the A. I. E. E., May 1928.

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6. "Transmission Line Engineering," W. W. Lewis, McGraw-Hill Book Co., Chapter VII.

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## Discussion

For discussion of this paper see page 1147.

# Lightning Investigation on New England
## Power Company System

BY E. W. DILLARD[1]
Associate, A. I. E. E.

***Synopsis.**—An analysis of the surges recorded during 1927 on a 75-mi. 110-kv. double-circuit transmission line of the New England Power System is presented in this paper. The surges are classified according to cause of surge-voltage damping, extent, etc. General conclusions are drawn regarding the nature of surges and protection afforded by ground wires.*

### INTRODUCTION

In long overhead transmission systems lightning disturbances constitute the greatest hazard to service. Perfect relay operation, even if it could be maintained, does not accomplish a complete cure, for usually system surges cause difficulties to a large number of users. Increasing standards of service emphasize the necessity of studies of lightning phenomena.

In making such studies on the New England Power System, we have considered that three general classes of information should be obtained.

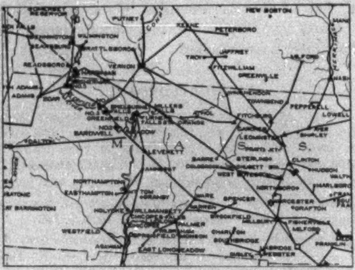
SOMERSET RESERVOIR
PUTNEY
NEW BOSTON
KEENE
PETERBORO
WILMINGTON
BRATTLEBORO
READSBORO
VERNON
TROY
JAFFREY
MILFORD
FITZWILLIAM
GREENVILLE
ADAMS
ZOAR
PEPPERELL
LOWELL
FITCHBURG
ATHOL
BARDWELL
DALTON
LEOMINSTER
SHIRLEY
M A S S.
LEVERETT
BARRE
STERLING
CLINTON
HUDSON
AMHERST
NORTHAMPTON
EASTHAMPTON
MT. TOM
GRANBY
WARE
SPENCER
WORCESTER
GRAFTON
HOLYOKE
WILLIMANSETT
BROOKFIELD
MILLBURY
PALMER
WESTFIELD
CHARLTON
SOUTHBRIDGE
MILFORD
FRANKLIN
SPRINGFIELD
MONSON
AGAWAM
EAST LONGMEADOW
WEBSTER

FIG. 1—PART OF NEW ENGLAND SYSTEM SHOWING HARRIMAN-MILLBURY LINE

1. Magnitude, extent, and character of lightning disturbances.
2. Protection afforded by ground wires.
3. Relative magnitude of surges of other than lightning origin.

### DESCRIPTION OF LINE

In an effort to get information of this nature records have been made of the surges occurring on the 110-kv. line of this company extending from Harriman, Vermont, to Millbury, Mass., a distance of 74.6 mi. A map of part of the system showing the Harriman-Millbury line is given in Fig. 1.

This line was chosen for investigation because of its unusual construction features. The general type of construction is shown by Fig. 2. Horizontal arrangement was used to give better performance under sleet conditions, lessen the chances of arcs blowing from phase to phase, and to give a lower height of conductors above ground. A ground wire was installed over one circuit only. The characteristics of the line are:

| | |
|---|---|
| Circuits | Two three-phase |
| Length | 74.6 mi. |
| Operating voltage | 110 kv. |
| Frequency | 60 cycles |
| Insulator—suspension | 8 disks |
| Insulators—strain | 9 disks |
| Conductors | 4/0 copper |
| Ground wires | One 7/16-in. crucible steel |
| Transpositions | Nine (three complete rolls) |
| Conductor spacing | 12 and 13 ft. |
| Average height of conductors above ground (entire line) | 42.15 ft. |
| Maximum elevation above sea level | 2100 ft. |

### SURGE-VOLTAGE RECORDER INSTALLATION

Through cooperation with the General Electric Company, surge-voltage recorders were installed and operated during the summers of 1926 and 1927. There was very little lightning in 1926 after the recorders were installed. During 1927 unusually severe lightning conditions were experienced and only 1927 surge-voltage records are discussed in this paper. Surge-voltage

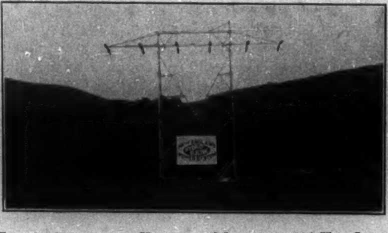

FIG. 2—TOWER ON HARRIMAN-MILLBURY 110-KV. LINE

records are supplemented by operating data of this and other years.

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[1] Electrical Engineer, New England Power Company.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

A total of twenty surge recorders was installed. Fig. 3 shows the location of the instruments. Three were installed on the north line at Harriman, six at the first intermediate station, two at the second intermediate station, six at the third intermediate station, and three on the south line at the Millbury station. Fig. 4 is a photograph of the installation at an intermediate station. Fig. 5 shows a typical record obtained.

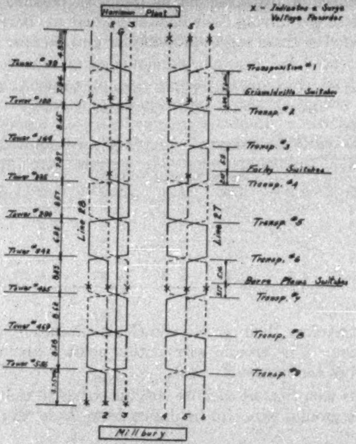
Harriman Plant
X - Indicates a Surge Voltage Recorder
1
2
G
3
4
5
6
Tower #38
Tower #100
Tower #164
Tower #469
Transposition #1
Transp. #2
Transp. #3
Transp. #4
Transp. #5
Transp. #6
Transp. #7
Transp. #8
Transp. #9
Barre Plains Switches
Line 28
Line 27
Millbury

FIG. 3—DIAGRAM OF HARRIMAN-MILLBURY LINE

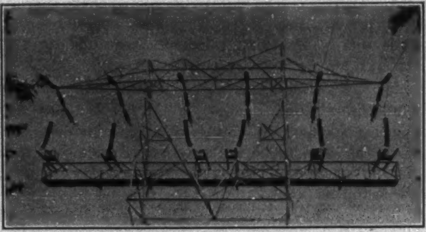

FIG. 4—SURGE-VOLTAGE RECORDER INSTALLATION

## RESULTS

A total of 155 surge voltages was recorded between June 6, 1927, and October 10, 1927. These may be classified according to origin and maximum recorded voltage as follows:

| | | |
|---|---|---|
| Lightning | 104 | maximum 900 kv. |
| Switching | 29 | maximum 360 kv. |
| Unknown | 22 | maximum 270 kv. |

Fig. 6 shows the number of surges recorded at various voltages. Only about 20 per cent of the recorded lightning surges were above 450 kv. No surge-voltage recorder indicated a high enough voltage to cause an insulator flashover, but during this period 47 trip-outs were experienced on the line. It is believed this observation indicates high decrement of lightning voltages rather than any inaccuracy of measurement.

Fig. 7 shows the number of surges at various voltages segregated according to amount of damping. The 104 lightning surges can be classified according to nature as follows:

| | | |
|---|---|---|
| Highly damped | 71, | Maximum 900 kv. |
| Slightly damped | 19, | Maximum 670 kv. |
| Highly damped and slightly damped, mixed | 14, | Maximum 900 kv. |

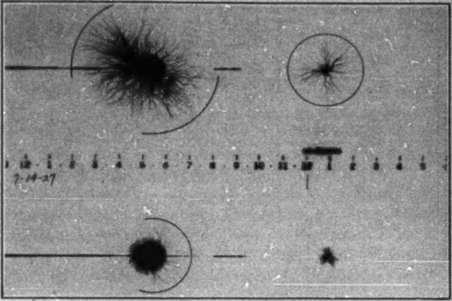

FIG. 5—SURGE-VOLTAGE RECORDER FIELD RECORD

At left, large highly-damped figure from lightning, small slightly-damped figure superimposed. At right small highly damped figure from lightning.

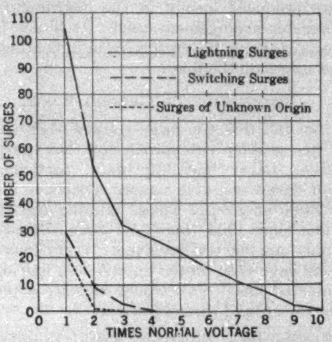

FIG. 6—NUMBER OF SURGES OF DIFFERENT ORIGINS WHICH EXCEED VARIOUS TIMES NORMAL VOLTAGE VALUES

| Cause of surge | No. highly damped | No. slightly damped | No. highly damped and slightly damped |
|---|---|---|---|
| Lightning | 71 | 19 | 14 |
| Switching | 27 | | 2 |
| Unknown | 10 | 12 | |

These results indicate a preponderance of highly damped surges both in regard to magnitude and to number. The inference to be drawn from this fact is that the surges most likely to cause flashovers are unidirectional. The origin of the slightly damped surges is not definitely known. There are indications that they are produced locally in the instrument by the potentiometer arrangement used. It is not felt that these records should be interpreted as indicating slightly damped surges on the line.

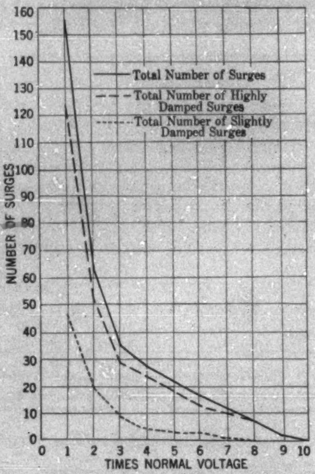

Fig. 7—Number of Surges at Various Times Normal Voltage

### Protection of Ground Wire

It is not felt that the surge-voltage-recorder data in regard to ground-wire protection are particularly conclusive. Other operating data, particularly the record of flashovers, give a more conclusive indication of the value of ground wires. During the operation of the line, since 1924, there have been 57 flashovers in which only one line was involved. Forty-four of these flashovers have been on the unprotected line and 13 on the protected line. This would indicate a protective ratio for the ground wire of 3.4 to 1.

It is probable that the surge-recorder tests would have been more conclusive on this point if they had been more comprehensive. The information obtained in these tests is also confused by the fact that the lines are transposed.

Data from one of the intermediate stations, Barre, at which recorders were installed on all six conductors are shown in the following table. In order to eliminate the effect of transposition as much as possible, only those surges having their highest voltage at Barre are included as these surges probably originated near Barre and therefore their records were least affected by transposition. The ground wire at this point is above and between conductors 2 and 3.

Surge Voltages Having Their Highest Value at Barre
Ground Wire is Above Conductors 2 and 3.

| Surge No. | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| | | | Times Normal Voltage | | | |
| 59 | 5.2 | 3.9 | 3.3 | 2.2 | 4.2 | 4.2 |
| 66 | 9.0 | 3.9 | 6.5 | 3.8 | 6.0 | 6.1 |
| 88 | 3.1 | 2.5 | 4.0 | 2.8 | 3.5 | 5.3 |
| 113 | 2.8 | 2.7 | 3.2 | 2.8 | 2.7 | 8.3 |
| 114 | 4.0 | 2.8 | 3.9 | 5.0 | 5.5 | 8.3 |
| Average | 4.8 | 3.1 | 4.2 | 3.3 | 4.4 | 6.4 |

It is seen that no definite conclusions as to the value of the ground wire can be drawn from these results.

### Conclusions

1. On this system during the period of the investigations practically all surge voltages of appreciable magnitude due to lightning were unidirectional or highly damped and of negative polarity.

2. No switching surge of greater than four times normal was found.

3. The maximum voltage of a lightning disturbance does not seem to be impressed over more than a very limited portion of the line. More study should be given to this point.

4. The data collected by the surge-voltage recorder do not allow definite conclusions to be drawn relative to ground-wire protection. Other data from operating records indicate worth-while protection.

## Discussion

For discussion of this paper see page 1147.

# Surge-Voltage Investigations on the 140-Kv. System of the Consumers Power Company During 1927

BY J. G. HEMSTREET*
Associate, A. I. E. E.
and
J. R. EATON*
Associate, A. I. E. E.

***Synopsis.**—During the past four years, the Consumers Power Company has been making studies of surge voltages on its 140-kv. system in Michigan. Previous Institute papers have summarized the results of these investigations up to the end of 1926. This paper describes the system, outlines the studies made during the summer of 1927, and presents the results obtained during that season.*

### INTRODUCTION

IN an effort to learn more of the electrical behavior of transmission lines, particularly under transient conditions, the Consumers Power Company and the General Electric Company conducted a cooperative investigation on the Power Company's 140-kv. transmission lines during the summer of 1927. Surge voltage recorders were connected to the lines at various points in order to measure the magnitude and time of occurrence of transient voltages. Data obtained from these instruments were correlated with system operation and disturbances as recorded in the load despatchers log.

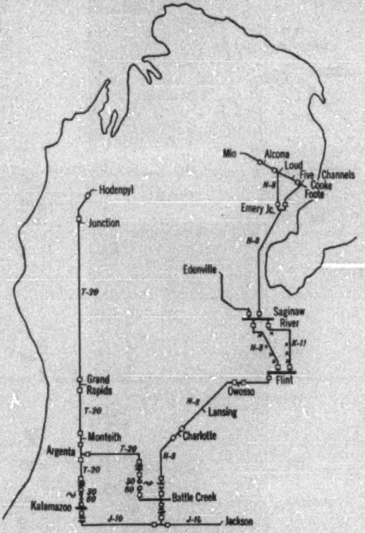
Mio
Alcona
Loud
Five
Channels
Cooke
Foote
H-8
Emery Jc.
H-8
Hodenpyl
Junction
T-20
Edenville
Saginaw
River
H-8
K-11
Flint
Grand
Rapids
T-20
Owosso
H-8
Lansing
Monteith
Charlotte
Argenta
T-20
H-8
T-20
30
60
30
60
Battle Creek
Kalamazoo
J-10
J-11
Jackson

FIG. 1—CONSUMERS POWER CO., 140-KV. TRANSMISSION SYSTEM 1927

□ Oil circuit breakers
X Surge-voltage recorder stations

### DESCRIPTION OF SYSTEM

The 140-kv. interconnected system of the Consumers Power Company is shown diagramatically on the map of the State of Michigan, Fig. 1. The system consists of three distinct parts interconnected through frequency changers and transformer banks:

1. The 140-kv., 30-cycle lines on the western side of the state from Hodenpyl Dam through Grand Rapids to Kalamazoo and Battle Creek. (Known as T-20)

2. The 140-kv., 60-cycle lines from Kalamazoo through Battle Creek to Jackson. (Known as J-10)

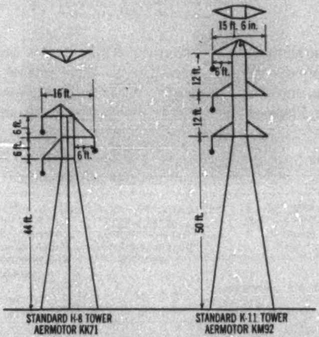
15 ft. 6 in.
16 ft.
12 ft.
6 ft.
12 ft.
6 ft.
6 ft.
6 ft.
44 ft.
50 ft.
STANDARD H-8 TOWER
AERMOTOR KK71
STANDARD K-11 TOWER
AERMOTOR KM92

FIG. 2—STANDARD TOWERS
H-8 and K-11 lines

3. The 140-kv., 60-cycle lines from Mio and Edenville through Saginaw and Flint to Battle Creek. (Known as H-8, K-11, and Edenville)

The 140-kv. system is operated with isolated neutral throughout. Numerous spur lines of lower voltages feed from the various stations on the 140-kv. system.

### TRANSMISSION LINES ON WHICH INSTRUMENTS WERE INSTALLED

The surge-voltage investigation was conducted on the H-8 and K-11 lines between Saginaw River Steam Plant and Flint. Under normal conditions, these two lines operate in parallel, being tied together at the substation buses. The design characteristics of these lines are shown in Table I. At the beginning of the summer neither line was equipped with a ground wire, but during the summer a ground wire was strung in place over the K-11 line. As these two lines are relatively close together, they are subjected to about the same storm conditions.

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*Both of the Consumers Power Co., Jackson, Mich.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

Eighteen surge-voltage recorders were installed on the lines as shown by the diagram of Fig. 4. On each line, instruments were connected to all three phases at two towers, one of which was 2½ mi. from the Saginaw River Steam Plant and the other about 3½ mi. from Flint.

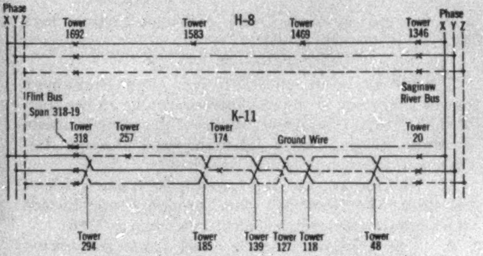
Phase
X Y Z
Tower 1692
Tower 1583
H-8
Tower 1469
Tower 1346
Phase
X Y Z
Flint Bus
Span 318-19
Saginaw River Bus
K-11
Tower 318
Tower 257
Tower 174
Ground Wire
Tower 20
Tower 294
Tower 185
Tower 139
Tower 127
Tower 118
Tower 48

FIG. 3—TRANSPOSITIONS AND RECORDER LOCATIONS

H-8 and K-11 lines
X Indicates surge-voltage recorder

TABLE I
DESIGN CHARACTERISTICS OF H-8 AND K-11 LINES

| | H-8 | K-11 |
|---|---|---|
| Length, miles | 38 | 44 |
| Type of construction | Steel tower | Steel tower |
| Type of tower | Aermotor KK-71<br>Single-circuit tower (see Fig. 2) | Aermotor KM-92<br>Double-circuit tower<br>One circuit erected (see Fig. 2) |
| Height of top conductor at tower, ft | 52 | 70 |
| Number of towers per mile | 10 | 8 |
| Configuration of conductor | · · · | ⋮ |
| Conductor[1] | 115,000-cir. mil copper | 3/0 copper (167,800 cir. mil) |
| Insulation[1] | 10-OB No. 25,622<br>10-OB No. 10,566 mixed | 9 OB No. 25,622 |
| Arc protection[1] | None | OB flux control |
| Ground wire* | None | 3/8 in. copper weld |
| Transpositions | None | See Fig. 3 |
| Relays at Saginaw and Flint[2] | Trip-out on ground (CR)<br>Trip-out on overload (CZ)<br>Both directional | Same<br>Same<br>Same |
| Character of ground | Flat | Flat |
| Soil | Clay to sandy loam | Clay to sandy loam |
| Lightning arresters | Lightning arresters are installed at every station on the 140-kv. system except at Emery Jct. and Argenta. They are of various makes. | |

*Ground wire on K-11 line strung in position between June 12 and August 14, 1927.

Two additional recorders divided the intervening line into three approximately equal parts. At the tower nearest Flint on the K-11 line and in the middle of the adjoining span, surge recorders were installed to measure any voltage which might appear between the ground wire and the ground. Typical installations are shown in Figs. 5, 6, and 7.

## SURGE-VOLTAGE RECORDERS

The surge-voltage recorder used in the investigation was a two-electrode instrument which measured all transients by positive Lichtenberg figures.[3] Connection to the line was made through a capacitance potentiometer consisting of a string of 15 standard suspension insulators, one end of which was connected to the line and the other end grounded. Instrument potential was obtained by a connection to the cap of the second insulator from the grounded end of the string. The recorders on the ground wire were directly connected, giving the same voltage on the instrument terminals as was built up on the ground wire.

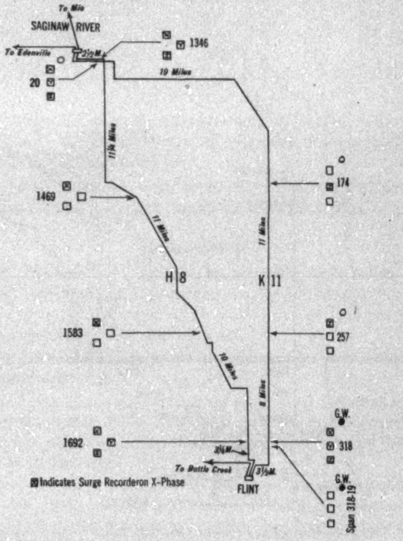
To Mio
SAGINAW RIVER
To Edenville
2½ M.
1346
20
10 Miles
11½ Miles
1469
174
11 Miles
11 Miles
H 8
K 11
1583
257
10 Miles
8 Miles
G.W.
1692
318
3¼ M.
To Battle Creek
3½ M.
FLINT
G.W.
Span 318-19
☒ Indicates Surge Recorder on X-Phase

FIG. 4—LOCATION OF SURGE-VOLTAGE RECORDERS

H-8 and K-11 lines
Showing distances between stations

## DURATION OF THE INVESTIGATION

All surge-voltage recorders on the line conductors were put in service on May 31 and June 1, and those on the ground wire, on July 8, 1927.

On September 14, two instruments were stopped,

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1. For references see bibliography.

and on September 20 and 21, the remaining recorders were taken out of service.

### RESULTS

During the period of the investigation, 219 surge voltages, classified as to origin as given in Table II, were recorded.

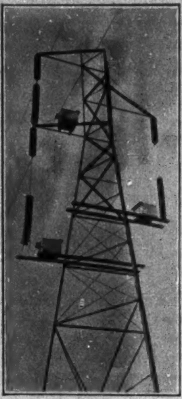

FIG. 5—TYPICAL SURGE RECORDER INSTALLATION
H-8 line

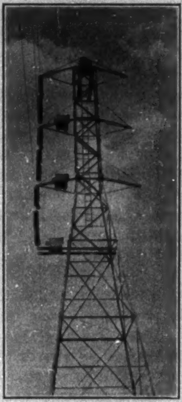

FIG. 6—TYPICAL SURGE RECORDER INSTALLATION
K-11 line
Showing recorder connected to ground wire

### SURGE VOLTAGES DUE TO LIGHTNING

*Number and Magnitude.* During the investigation, 76 surge voltages, which were attributed to lightning, were recorded. The number of these surges, exceeding various times normal values, is shown by the curves of Fig. 8. It will be noted that only 20 per cent of the recorded voltages exceeded five times normal. (570 kv.)

*Polarity.* Surges voltages attributed to lightning are classified as to polarity in Table III.

These data indicate that all lightning surge voltages of appreciable magnitude on this particular system were oscillatory during the period of the tests. This statement cannot be made as a definite conclusion because of several factors among which are:

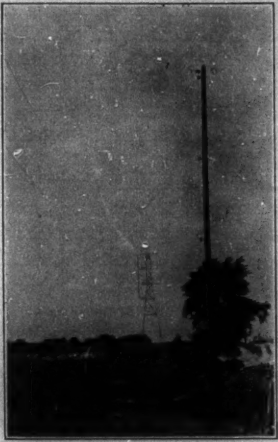

FIG. 7—SURGE RECORDER INSTALLATION AT MID-SPAN OF GROUND WIRE
K-11 line

TABLE II
CLASSIFICATION OF SURGE VOLTAGES

| Origin | Number | Highest crest value | |
|---|---|---|---|
| | | Times normal | Kv. |
| Lightning | 76 | 10.0 + | 1140 |
| Switching | 93 | 3.3 | 375 |
| Accidental short circuits and grounds | 1 | 3.6 | 410 |
| Unknown | 49 | 5.7 | 640 |
| Total | 219 | | |

Note: Normal crest voltage to ground = 114 kv.

1. The possibility of reflections with reversed polarity of voltage.

2. Possibility of secondary oscillatory surges resulting from circuit-breaker operation.

3. Because of limitations of the instrument, two unidirectional surges of opposite polarity, occurring

with little intervening time interval, record as one oscillatory surge voltage.

*Nature.* Lichtenberg figures of three different natures were recorded by lightning surge voltages: highly damped (H. D.), medium damped (M. D.), and slightly damped (S. D.). The highly damped figures are interpreted as having been produced by surge voltages which were of extremely short duration, lasting for only a few polarity reversals. The medium damped figures are produced by surge voltages which are less rapidly damped and may last for an appreciable length of time. Such surge-voltage registrations in almost every case correlated with arc-over from line conductor to ground and with automatic circuit breaker operation. These medium damped figures apparently are peculiar to the isolated neutral system, and are probably produced by line oscillations following flashover. The slightly damped figures are of uncertain origin and seem to be dependent upon the type of potentiometer with which the surge recorder is connected to the line. In view of this uncertainty, conclusions drawn from slightly damped figures are open to question. Continued laboratory studies should lead to an accurate interpretation of the slightly damped figures. The number and magnitude of lightning surge voltages under the above classification are shown in Table IV.

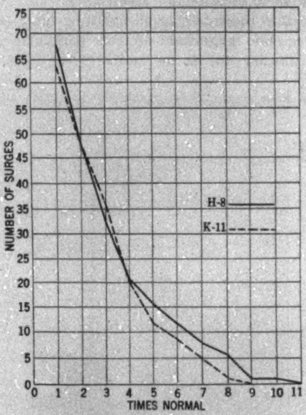

Fig. 8—Number of Lightning Surge Voltages Exceeding Various Times-Normal Values

Entire season
H-8 and K-11 lines

TABLE III
POLARITY OF LIGHTNING SURGE VOLTAGES

| Polarity | Number | Highest crest value | |
|---|---|---|---|
| | | Time normal | Kv. |
| Unidirectional | | | |
| Positive | 1 | 1.9 | 216 |
| Negative | 3 | 1.2 | 137 |
| Oscillatory | | | |
| Highest crest value | | | |
| Positive | 28 | 8.4 | 960 |
| Negative | 20 | 7.5 | 855 |
| Positive and negative crest values equal | 24 | 10.0 + | 1140 + |

TABLE IV
NATURE OF LIGHTNING SURGE VOLTAGES

| Nature | Number | Highest crest value | |
|---|---|---|---|
| | | Time normal | Kv. |
| H. D. | 13 | 7.5 | 855 |
| M. D. | 10 | 7.7 | 877 |
| S. D. | 16 | 7.8 | 890 |
| H. D. M. D. mixed | 12 | 7.1 | 810 |
| H. D. S. D. mixed | 7 | 7.3 | 832 |
| M. D. S. D. mixed | 11 | 8.8 | 1000 |
| H. D. M. D. S. D. mixed | 7 | 10.0 + | 1140 + |
| Total | 76 | | |

Surge voltages which were recorded by highly damped or slightly damped figures were very similar as regards magnitude and extent over the transmission system. In almost all cases such disturbances were confined to less than 20 mi. of line. The magnitude of surge voltages recorded by medium damped figures was slightly less than the magnitude of those producing highly damped or slightly damped figures, but they were quite different in that they recorded with almost equal value at all instrument locations.

*Attenuation Along the Line.* As pointed out above, surge voltages of medium damped characteristics are recorded with almost equal magnitudes at all recorder stations, and hence show practically no attenuation along the line. Surge voltages recorded by either slightly damped or highly damped figures showed considerable reduction in magnitude from one instrument station to the next. Surge voltages of the highly damped type in some cases reduced from 250 kv. to 0 kv. in 10 mi., or at the average rate of 25 kv. per mile. Those recorded by slightly damped figures, in some cases reduced from 900 kv. to 300 kv. in 10 miles, or at an average rate of 60 kv. per mile.

Comparison of insulator flashover to surge voltage recorder data showed that in some cases the voltage reduced from a value sufficient to cause insulator flashover (about 1000 kv.) to 500 kv. in distances of 4 to 10 miles. This indicates average reductions in voltage between 50 and 125 kv. per mile.

*Protective Value of the Ground Wire.* During the investigation, a ground wire was strung in place over the K-11 line, making possible a study of the operation of this line with and without a ground wire, and a comparison of its performance to that of the H-8 line which has no ground wire. Fig. 9

shows the number and magnitude of surge voltages recorded on the H-8 and K-11 lines before the ground wire was completely installed on the K-11. These curves indicate that during that period, the voltages recorded were about equally severe on the two lines. The curves of Fig. 10 show the number and magnitude of the surge voltages recorded after the ground wire was installed. It will be noted that during this period, the recorded surge voltages were considerably less severe on the K-11 than on the H-8.

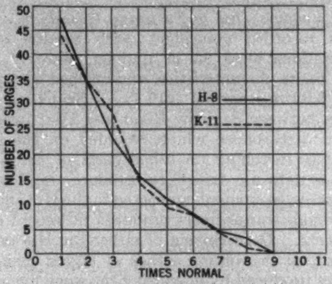

Fig. 9—Number of Lightning Surge Voltages Exceeding Various Times-Normal Values

Before ground wire was installed on K-11 line

*Relation of Conductor Height to Voltage Measured.* The curves of Fig. 11 and 12 show the magnitude and number of surge voltages recorded on the top, middle, and low conductors of the H-8 and K-11 lines, respectively, using only the data obtained at those stations where instruments were installed on all three conductors. From these curves, it is seen that no definite relation exists between the magnitude of surge voltages measured and conductor height. It is thought that transpositions in the line, reflection of the transient waves, and other factors, so complicate this study that voltages measured at a few recorder stations do not give a true indication of the relative voltages induced at the origin of the lightning disturbances.

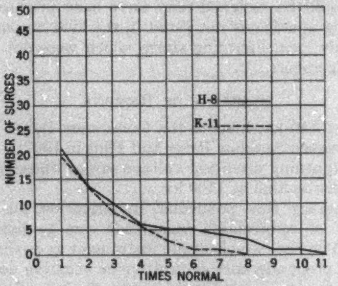

Fig. 10—Number of Lightning Surge Voltages Exceeding Various Times-Normal Values

Ground wire on K-11 line

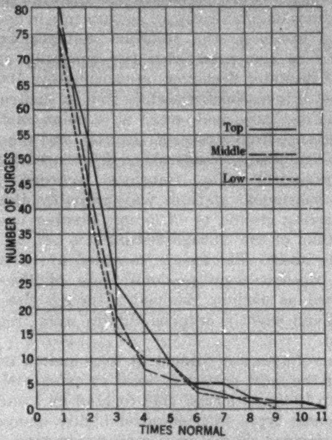

Fig. 11—Number of Lightning Surge Voltages Exceeding Various Times-Normal Values, Recorded on Top, Middle, and Low Conductors

H-8 line

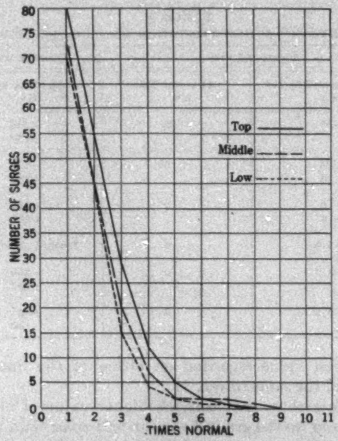

Fig. 12—Number of Lightning Surge Voltages Exceeding Various Times-Normal Values, Recorded on Top, Middle, and Low Conductors

K-11 line

*Surges Coincident with Switch Trip-Out.* In every case of switch trip-out on the 140-kv. system, surge voltages were recorded at one or more of the surge recorder stations. Trip-outs of the H-8 or K-11 lines between Saginaw River and Flint produced registrations on practically all instruments in operation. In some instances, the recorded voltages were low (400 kv.) as compared with the generally accepted value of insulator flashover (approximately 1000 kv.). However, it is reasonably certain that in such cases, the lightning discharge took place at a point on the line some distance from a recorder station, and the voltage wave attenuated considerably before reaching the first instrument. The transient recorded at the various instrument stations was probably the result of the arcing ground or of circuit breaker operation, rather than of the voltage disturbance set up by the lightning itself. The figures recorded at the time of switch trip-outs were predominately of the nature designated as medium damped, although also highly damped and slightly damped figures were frequently recorded.

Surge voltages not coincident with switch trip-outs were for the most part very local in extent, of values from 1 to 10 times normal (114 to 1140 kv.) and of all three figures types with those of highly damped and slightly damped characteristics predominating.

*Surge Voltages on the Ground Wire.* Table V shows the lightning surge voltages recorded on the ground wire at mid-span and at the tower, and the highest value recorded on either of the line conductors at the same tower.

TABLE V
LIGHTNING SURGE VOLTAGES ON GROUND WIRE

| On ground wire | | On conductor |
|---|---|---|
| At mid-span 318-319 Kv. | At tower 318 Kv. | At tower 318 Kv. |
| +35+ | +28 | +206<br>−160 |
| +24<br>−16 | 0 | −456<br>+285 |
| − 6<br>+ 4 | 0 | −410<br>+285 |
| +5.5 | 0 | Record obscured |
| −3.7 | 0 | −850<br>+182 |
| +2.0 | 0 | +205<br>−160 |

The data show that a much higher value of voltage may appear on the ground wire at mid-span than at the tower, possibly due to the finite length of time required for the transient to travel along the wire to ground at the tower.

*Line Failures.* During the operation of the surge recorders lightning caused failure of the H-8 line about 50 mi. southwest of Flint when an insulator flashover burned off one of the conductors, permitting it to short-circuit with the conductor below and to fall to the ground. Automatic circuit-breaker operation cleared the section of line in trouble. The disturbance produced a registration on all but two of the instruments on the line conductors. In general, the surge recorded was of moderate value, but on $Y$-phase, tower 1692 of the H-8 line it reached a value of 7.7 times normal (880-kv.).

*Surge Voltages Due to Switching Operations.* Surge voltages recorded coincident with routine switching operations were 92 in number, were of highly damped figure characteristics, and reached a maximum value of 3.6 times normal (410 kv.). Switching on the two lines between Saginaw River and Flint invariably produced disturbance which recorded on the instruments, but switching on other parts of the 140-kv. system sometimes failed to produce registrations. Switching on equipment connected to the H-8 and K-11 lines through transformers produced no record on the instruments. Deenergizing of either the H-8 or K-11 lines resulted in voltage surges of higher magnitude than were produced by energizing the same line.

*Surge Voltages from Unknown Causes.* During the season, 49 surge voltages were recorded for which no cause could be assigned. These voltage disturbances were all oscillatory and, for the most part, very local in extent. They were of relatively small magnitude, the majority being less than 3.0 times normal (340 kv.), and the most severe 5.7 times normal (650 kv.). Surge voltages of highly damped, medium damped, and slightly damped characteristics were about equal in number.

It is thought that these surge voltages for which no cause could be assigned may have been produced by switching operations not listed in the load despatchers log, or by local lightning storm which were not noted by the operators.

## SUMMARY OF RESULTS

On the 140-kv. lines of the Consumers Power Company between Saginaw River and Flint in 1927:

1. Lightning produced voltage surges whose magnitudes were as high as 1100 kv.
2. During this particular investigation, all surge voltages of appreciable magnitude due to lightning recorded on the two-electrode instrument as oscillatory, with no preponderance of positive or negative polarity indicated. In a number of cases, the record of the surge from the lightning itself was undoubtedly considerably obscured by secondary oscillations from arcing grounds and circuit breaker operation.
3. The surge voltages due to lightning were characterized by three different figure types; highly damped, medium damped, and slightly damped.
4. Surge voltages characterized by medium damped figures showed very little change in value from station to station, and frequently correlated with arcing grounds and switch trip-outs.

5. Comparison of simultaneous registrations of highly damped and slightly damped surge voltages showed the reduction in voltage from station to station to be of the order of 50-kv. per mi. From insulator flashover, the attenuation appeared to be in the order of 100 kv. per mile.

6. The data indicated that the ground wire afforded some protection against lightning disturbances.

7. No definite relation was shown between conductor height and voltage recorded.

8. Surge voltages recorded coincident with switch trip-outs due to lightning frequently were of a magnitude less than 400 kv., though higher voltages undoubtedly existed on the line at points remote from recorder stations.

9. Lightning surges which produced no switch trip-outs were, as a rule, very limited in their extent although they were frequently of a very high value. (800-1100 kv.).

10. Under lightning conditions, voltages in excess of 35 kv. were built up between ground wire and ground at mid-span, without excessively high voltage on the line conductors. The voltage from ground wire to ground was always considerably less at the tower than at mid-span.

11. Normal switching operations produced surge voltages of low value which extended over considerable length of line.

12. Numerous surge voltages were recorded which could not be correlated with lightning storms or system switching. The magnitudes of such disturbances were relatively low, reaching values no higher than 5.7 times normal (650 kv.).

### ACKNOWLEDGMENTS

The writers wish to acknowledge the assistance of members of the General Engineering Laboratory and Central Station Engineering Department of the General Electric Company, in conducting the investigation and in preparing this paper.

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## Discussion

For discussion of this paper see page 1147.

# Surge Voltage Investigation on the 132-Kv. Transmission Lines of the American Gas and Electric Company

BY PHILIP SPORN[1]

Member, A. I. E. E.

*Synopsis.—Data on the surge voltage investigation, carried out under the auspices of the Subcommittee on Lightning, on one of the 132-kv. lines of the American Gas and Electric Company during 1928, are presented. Most of the surges have been segregated as to cause, and plotted in summary form for more convenient use. The magnitude and character of recorded surges are discussed; and the conclusions drawn from data presented.*

*Information on voltage surges due to lightning, switching, trip-outs, and unknown causes are presented, as well as records of lightning arrester discharge currents, voltages across choke coils, and on the ground wire.*

*This paper is presented at this time to make available to the engineering profession some of the information obtained, before the report of the Subcommittee on Lightning is completed. As experimental work is still being done in the field during 1928, anything like a complete report cannot be made until next year.*

## I. INTRODUCTION

IN carrying out the work of the Subcommittee on Lightning of the Transmission and Distribution Committee of the A. I. E. E. with the author as Secretary, an extensive klydonograph layout was planned and placed in operation on the 132-kv. system of the American Gas and Electric Company during the lightning season of 1927. This work, started under the sponsorship of the Subcommittee on Lightning, was made possible by the cooperation of the General Electric Company, the Westinghouse Electric and Manufacturing Company, and the American Gas and Electric Company, and the subsidiaries of the latter, namely, the Ohio Power Company and the Appalachian Electric Power Company.

This paper presents some of the first data obtained from the investigation on one part of the system. It is planned to combine with all the 1927 work, data from other parts of the system, where the investigation was carried on, together with results secured from the continuation of tests during 1928, and present it later as a complete report by the Lightning Subcommittee.

## II. SYSTEM INVESTIGATED

In selecting a system on which to carry on this work during 1927, the Lightning Committee decided the 132-kv. Philo-Canton line of the American Gas and Electric Company was particularly well suited, as this line had experienced a great deal of lightning trouble when first placed in service.[2] It had been supplied, after careful study, with protective equipment designed to minimize lightning troubles; and it was situated in a section of the country where lightning storms were known to be unusually severe.

The Philo-Canton line is a 73-mi., double-circuit A. C. S. R. conductor line, with wires in vertical configuration, one circuit on each side of the tower. The line is equipped with ring and horn protection on all insulator strings, and with one ground wire at the peak of the tower. This line is in Ohio, parallel to, and about 50 mi. west of the Ohio River. The 123-kv. system is operated with solidly grounded neutral, the only ground on the Philo-Canton line being at the Philo end.

In carrying out the program, tests were made also on a 132-kv. lightning arrester at the Turner substation located in Charleston, West Virginia.

This paper covers only results obtained on the Philo-Canton line and on the lightning arrester at Turner substation.

## III. SCOPE OF INVESTIGATION

In planning the installation of instruments, locations were so chosen that it was expected valuable information would be obtained on the following:

1. Choke coil effectiveness.
2. Ground wire protection.
3. Polarity of lightning.
4. Transient voltages on the ground wire.
5. Functioning of lightning arresters.
6. Attenuation of voltage surges.
7. Voltage change at termination of ground wire.
8. Switching surges.
9. Action of tower ground resistance during insulator flashover.
10. Relative surge voltages on symmetrically placed parallel conductor.

The first instruments were placed in service May 10, 1927, and the major part of the installation completed about June 15. The investigation as a whole was concluded October 16, 1927, although some of the instruments at the stations, where they were accessible, were continued in operation throughout the winter of 1927-1928.

## IV. LOCATION OF INSTRUMENTS

The general location of klydonograph is shown in Fig. 1. The set-up included 37 G. E. double reverse electrode surge recorders and one Westinghouse four-electrode klydonograph. As connected, the instru-

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[1] American Gas and Electric Company, New York, N. Y.

[2] *Lightning and Other Experience with 132-Kv. Steel Tower Transmission Lines,* Sindeband and Sporn, A. I. E. E. TRANS., Vol. 45, 1926, p. 770.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

ments were capable of recording surges at 40 different points on the system. It was realized, of course, that while instruments were located with a definite object in view, they would obviously record any and all surges on the line and therefore, information other than that specifically planned for would be obtained.

In analyzing the layout, reference to Fig. 1 shows that stations Nos. 1 and 5, also 32 and 33, were located to determine the voltage change across choke coils. Ground wire protection data were expected from instruments 7 to 19, 21 to 23, 33, 34, and 35. From the instruments located at Stations 7 to 19, inclusive, it was expected that some information would be obtained on the attenuation of surges. Data on voltage characteristics at the termination of ground wire were expected at Stations 5, 41, 7, 29, and 32. A lightning arrester study was undertaken by instruments at Stations 4, 5, 24, 30, 31, and 38. At Station 42 an instrument was connected to the ground wire at the peak of the tower to measure the voltage on the ground wire. At Station 43, an instrument was connected from the base of the tower to an artificial ground system made from ground rods located at least 10 ft. from the base of the tower. This set-up was made to determine, if possible, any voltage change between the tower base and normal ground due to any drop through the tower ground resistance in case of flashover at this tower. Another interesting set-up is at Tower 172 including Stations 20, 21, 22, and 23. This set-up was made to compare the two different types of instruments used and their couplings to the line. Station 20 is a three-electrode Westinghouse klydonograph coupled to the line with pipe type potentiometers and Stations 21, 22, and 23 are equipped with G. E. surge-voltage recorders coupled to the line with insulator string potentiometers.

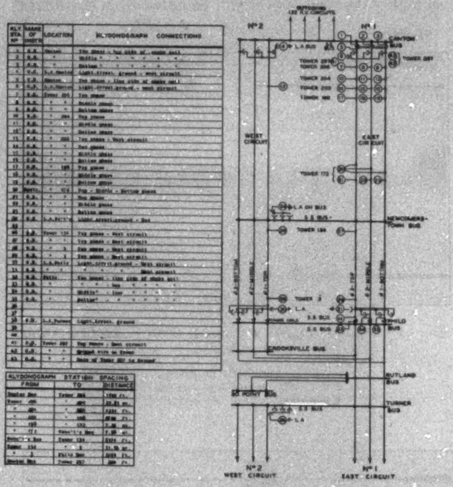

FIG. 1—KLYDONOGRAPH LAYOUT—132-KV. SYSTEM 1927 TESTS

Two typical set-ups of the instruments in the field at Stations 20, 21, 22, and 23 are shown in Figs. 7 and 8. Figs. 7 and 8 show the tap leads extending from the line to the klydonograph stations located at the base of the tower, both pipe type and insulator string potentiometers with klydonographs appearing clearly in the foreground.

The insulator string potentiometer connections at Stations 1, 2, 3, and 5 are shown in Fig. 9. The klydonograph is shown tapped across the lower insulator of the entire string. In the first part of the test the instrument was tapped across the two lower units, but this connection was later changed so as to tap one unit, thereby increasing the potentiometer ratio.

## V. POTENTIOMETER COUPLING TO 132-KV. CIRCUITS

The klydonograph and surge voltage recorder, the action of which is well known, has been described previously.[3] Since these instruments are suitable for connecting to a circuit, the crest voltage of which under surge conditions ranges from 1500 to 30,000 volts,[4]

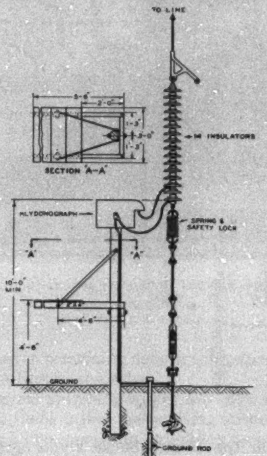

FIG. 2

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[3] *The Klydonograph and Its Application to Surge Investigation*, Cox and Legg, A. I. E. E. TRANS., Vol. 44, 1925, p. 857.

*The Measurement of Surge Voltages on Transmission Lines due to Lightning*, Lee and Foust, A. I. E. E. TRANS., Vol. 46, 1927, p. 339.

[4] The klydonograph will not record crest voltages below 1500, and flashes over around 30,000.

the instrument must be provided with suitable reduction equipment to connect to high-voltage circuits of the order of 132,000 volts (108,000 volts crest to ground). In these tests two types of potentiometers were used to reduce the normal line voltage to a voltage suitable for the instrument. One type, the insulator string potentiometer, is shown in Fig. 2, and consists essentially of 14 line insulators with the instrument tapped across the lower insulators on the ground end of the string. This type of potentiometer connected to the high voltage side of the circuit, was used with all G. E. surge recorders. The other type potentiometer shown in Fig. 3, was used on the Westinghouse klydonograph. This potentiometer consists essentially of four 3-in. pipes approximately ten feet long assembled with two strings of line type insulators. With the insulator string potentiometer a ratio of approximately 52/1 was secured when tapping the bottom insulator and 38/1 when tapping the bottom two insulators. The ratio used with the pipe type potentiometer was approximately 65/1. There are two main differences in these two types of potentiometers. First, with the insulator type the dielectric field is principally in porcelain, while with the pipe type it is mainly in the air. Second, the klydonograph is tapped across a part of the insulator string leakage path with the insulator string type potentiometer, but this is not the case with the pipe type of potentiometer.

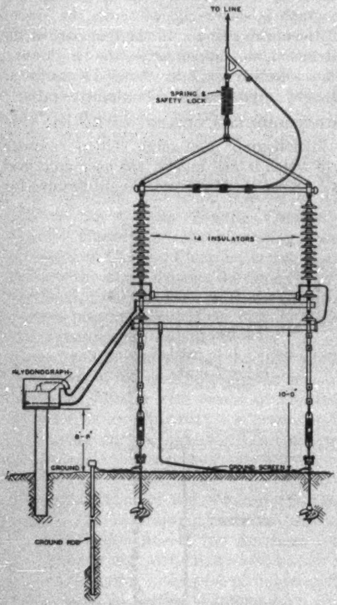


FIG. 3

## VI. CHARACTER OF SURGES

The general types of Lichtenberg figures obtained on all records are shown in Figs. 4, 5, and 6. In Fig. 4, surge 1 is a typical lightning figure, which is described as highly damped, and it will be noted from the figure that there is a large positive and a very small corresponding negative just observable above the normal voltage band (the large figure may be positive or negative, depending upon which electrode originally recorded it). Surges 2 and 4 are typical switching surges of a highly damped nature and indicate a rather high voltage, but with only a few reversals of high magnitude. This is clearly shown by the lack of density in the figures. Surges 3 and 5 are also switching

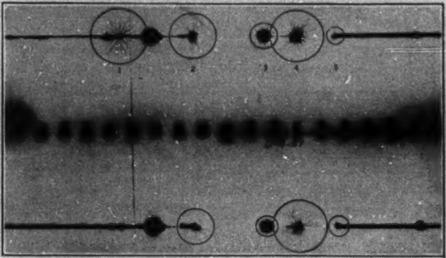


FIG. 4—SURGE-VOLTAGE RECORDER FIELD RECORD—OHIO POWER CO.

1 typical lightning (HD) figure
2 & 4 (HD) figures, line deenergized
3 & 5 (HD) figures, line energized

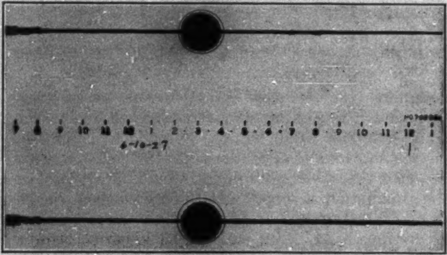


FIG. 5—SURGE-VOLTAGE RECORDER FIELD RECORD—OHIO POWER CO.

Typical (SD) figure

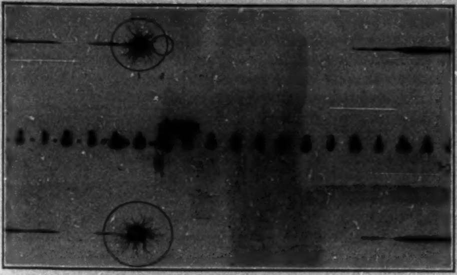


FIG. 6—SURGE-VOLTAGE RECORDER FIELD RECORD—OHIO POWER CO.

Special switching operation. 1—Line deenergized at Canton 2—Line energized at Canton

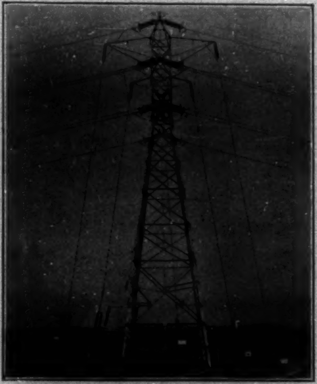


FIG. 7—FIELD INSTALLATION OF SURGE RECORDERS

Tower 172 showing line coupling
Philo-Canton 132-kv. line

8—FIELD INSTALLATION OF SURGE RECORDERS

Tower 172 showing line coupling
Philo-Canton 132-kv. line

surges of a lower magnitude with surge No. 3 showing a tendency for a sustained voltage considerably in excess of normal line voltage. A typical slightly damped figure is shown in Fig. 5. In general, this type of picture indicates an oscillatory voltage sustained for a relatively long period of time. Its reproduction in the laboratory has been approximated by normal frequency voltage for a period in the order of a minute. Although it has never been perfectly reproduced in the laboratory, such attempts as have been made seem to indicate it requires an oscillating voltage and also an appreciable element of time.

A number of this type of surge was obtained during the test period, but as their presence could not be explained, and since, as described later, they appeared to be a function of the potentiometer used, they have not been used in presenting data in this paper, except to indicate that they have existed.

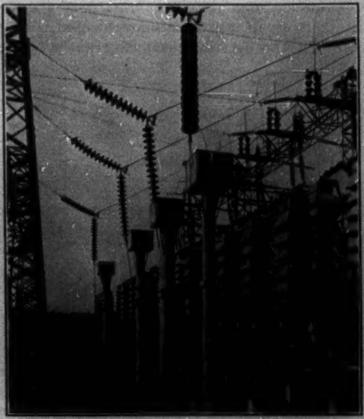


FIG. 9—SURGE RECORDER INSTALLATION

Canton 132-kv. station
Stations 1, 2, 3, and 5

Other typical switching surges are shown in Fig. 6, surge No. 1 being a line deenergizing surge and surge No. 2 being a line energizing surge both recorded at the Canton end of the line.

## VII. DATA OBTAINED AND ANALYSIS

During the period of instrument operation up to October 16, 1927, approximately 3600 Lichtenberg figures, resulting from 550 surges, were obtained on the Philo-Canton section of the system. These surges were classified and regrouped so that a detailed study might be made of any particular type of surge. On the Phil-Canton line these surges have been classified according to cause, as follows:

TABLE I

| | Total | Excluding slightly damped |
|---|---|---|
| Unknown origin | 295 | 272 |
| Outside switching | 29 | 26 |
| Pure switching surges | 101 | 101 |
| Lightning surges | 166 | 96 |
| Combined lightning and switching | 6 | 4 |
| Lightning arrester discharges | 40 | 40 |
| Ground wire surges | 68 | 68 |

*Outside and Pure Switching Surges.* For more convenient study, the surge data have been assembled into summary curves, two of which are shown in Fig. 10. The lower curve applies to outside switching surges and shows that of 26 surges the maximum was 1.8 times normal and that 50 per cent of them were over 1.4 times normal. Outside switching surges are classified as surges originating from switching on parts of the system other than where instruments are located. In some cases surges were caused by switching on the secondary side of the transformers connected to the 132-kv. line. This type of surge has also been included in this curve.

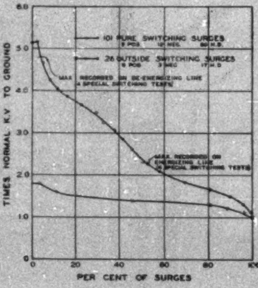


FIG. 10

The upper curve of this Fig. 10 shows the results of 101 pure switching surges with maximum recording value of 5.2 times normal. These surges have been segregated as to nature, showing 9 positive, 12 negative, and 80 highly damped. Two points of the curve have been marked, indicating the maximum recorded voltage on energizing; also on deenergizing the line. These two points were the results obtained on four separate switching tests of the Philo-Canton line, in which surges caused by energizing and deenergizing the line as well as switching load at Newcomerstown (the approximate half way point of the line) were separated by one hour intervals. In the earlier part of the tests it was found that lightning and switching surges occurring at the same time caused some confusion due to the absolute impossibility of separating the switching part of the surge from the lightning part. It was therefore decided to separate the switching surges by one hour intervals in a prearranged test and in this way study the effects of switching load, deenergizing the line, and energizing the line. Results show that the maximum recorded surge occurred on deenergizing the line and was 4.8 times normal. On energizing the line the maximum surge was 2.3 times normal.

To show the effect of the switching voltage throughout the entire length of the line, the records obtained on three of these switching surges are shown in Figs. 12 and 13. The point of interest is that the switching surge travels with apparently little change in the voltage throughout the entire length of the line. The irregularities in the curves are probably within the limits of accuracy in the instruments and the distinct tendency of higher voltages at either end of the line due to reflection will be noted.

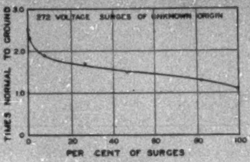


FIG. 11

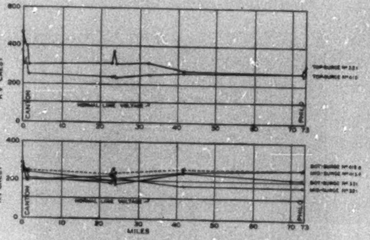


FIG. 12—PURE LINE SWITCHING SURGES

May 10 to Oct. 16, 1927
Philo-Canton 132-kv. line
Deenergized at Philo station

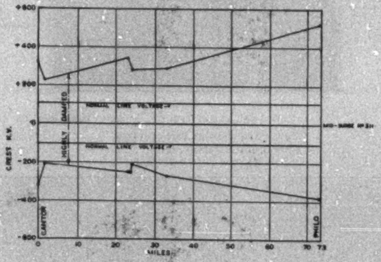


FIG. 13—PURE LINE SWITCHING SURGES

Philo-Canton 132-kv. line on July 30, 1927—11.00 p. m
Deenergized at Canton station

*Surges of Unknown Origin.* Surges of unknown origin on the Philo-canton line are shown graphically in Fig. 11. While there were 272 surges for which no cause could be found, it will be noted that these never exceeded 2.5 times normal and only five per cent of them exceeded two times normal. This type of surge can be dismissed as being unimportant in magnitude, although constituting a comparatively large number of voltage changes on the line.

*Lightning Surges.* The 96 lightning surges on the Philo-Canton line are summarized in Fig. 14. The maximum surge indicated is 4.4 times normal and 50 per cent of the surges are above one and one-half times normal. These surges have been segregated as to nature predominating in each surge, as follows: 25 negative, 42 positive, and 29 highly damped.

*Lightning and Lightning Surges.* The four lightning surges on the line causing line trip-outs, gave maximum voltages of 5.0 and 3.7 times normal to ground. These were slightly damped surges, and it is believed may have been caused by the switching surge following the lightning voltage flashover. The other two surges recorded a maximum of 5.4 and 6.2 times normal, but both being S. D. figures, the results were not seriously considered. Since lightning voltages over double the values recorded above are necessary to cause insulator flashover, it is clear, even with a fairly large number of instruments on the line, there is no certainty that anything like the maximum voltage on the line will be recorded. As sections of line in the order of 25 mi. existed where no surge recorder was located, this shows that the lightning voltages did not travel with destructive values any great distance. This characteristic of the lightning surge is distinctly different from the switching surge.

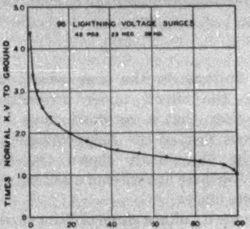


Fig. 14

*Voltage Drop Through Choke Coils.* The attempt to measure the voltage drop through choke coils was rather ineffective on account of the existence of S. D. figures in the records. However, of 10 lightning surges (no S. D. figures included) the bus side of the choke coil was the higher on four surges, averaging nine per cent higher than the line side and on six surges the line side of the choke coil was higher, averaging 25½ per cent higher voltage than on the bus side. It can only be said that a tendency exists, as indicated, for the choke coil to reduce the lightning voltage originating on the line in the order of 25 per cent, but it is not felt that sufficient data on this subject have been obtained to prove finally the effectiveness of the choke coil.

*Lightning Arrester Data.* The data on all six lightning arresters are summarized in Fig. 15. The only record of current discharge in the arresters was obtained at Newcomerstown and Turner substations. No records were obtained at Philo or Canton on lightning arresters due apparently to the arrester not discharging, although the instrument was set up to record a current as low as about 150 amperes in the neutral leg. In Fig. 15 it should be noted that the current and voltage are not simultaneous readings. Forty lightning arrester discharges were recorded; 21 were positive, 11 were negative, and 8 were highly damped. Of the lightning discharges 12 were positive, eight negative, and four highly damped. Of the switching discharges one was positive and one negative. Of the discharges due to unknown causes nine were positive, two negative, and two highly damped. One discharge due to an arcing ground registered minus 360 and plus 410 amperes, being of a highly damped nature. An attempt to plot a curve of current against voltage recorded resulted in a shotgun curve of little value. It is felt that considerably more work will have to be done in securing lightning arrester data before any definite conclusion is arrived at.

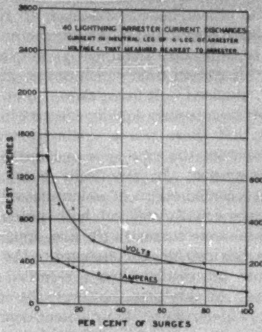


Fig. 15

*Lightning Surges on Parallel Circuits.* The data secured at instruments located on the top wires of the two Philo-Canton lines (eliminating S. D. figures) gave nine surges including four positive, two negative, and three highly damped. The ratio of the two lines at any point varied from 0.80 to 1.25, averaging 1.03. The minimum voltages occurring during these surges were in the order of 120 kv. to 140 kv. minimum to a maximum of 340 to 400 kv. The data here, again, are too meager to prove definitely that the induced voltages on the two wires are equal; but this tendency is indicated.

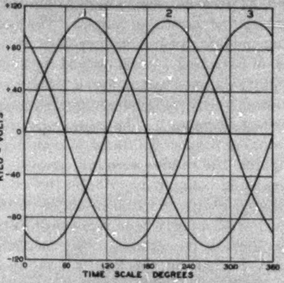
*Tower Base Voltages.* At Station 43 where an instrument was located to determine the voltage between the tower base and ground, no records were obtained during the season. It should also be noted that at this tower there were no flashovers of the line.

*Comparison of Potentiometer Couplings at Tower 172.* This location of instruments was made to give a comparison of instruments and of potentiometer couplings. Some 300 records were obtained on the instruments located at this station from which certain and definite data were obtained. It was shown that the two types of instruments were equally effective in recording surges, but that there was a distinctly troublesome difference between the pipe type and insulator string type potentiometer. In practically every case the instruments recorded surges of unidirectional or highly damped surges equally well on both potentiometers, but when there were surges on the line, apparently due to lightning, the instrument connected to the pipe type potentiometer practically always recorded unidirectional surges. At this time, however, the instrument connected to the insulator string potentiometer would frequently record surges of a slightly damped nature. That this occurrence was due to the potentiometer alone was definitely proved by coupling two separate instruments to the same point on the line, one through a pipe type and the other through an insulator string type potentiometer. Slightly damped surges, six and one-half times normal and above, were recorded at this station through the insulator string potentiometer which failed to indicate at all through the pipe type coupling. Slightly damped figures as low as 1.8 times normal have been recorded through the insulator string potentiometer which failed to give any record at all through the pipe type coupling.

A study of results secured at this tower led to the conclusion that all of the so-called slightly damped surges recorded in the investigation should be excluded from analysis and consideration, in a study of the data; and this practise has been followed in this report.

Study made subsequently in the laboratory confirmed the impression that the S. D. figures are brought about in some way by a condition in the circuit of the insulator string type potentiometer, and that while a surge occurrence on the line may set off the circuit that finally produces the S. D. figures, that no potential of the order generally indicated by the S. D. figures actually exists on the line itself. All the laboratory work failed to disclose a means whereby an S. D. figure could be actually reproduced. As a consequence, the conclusion was reached to disregard the S. D. figures obtained on the insulator string potentiometer on past work, and in future work to adhere either to the pipe type potentiometer or to a modification of the string potentiometer that would definitely preclude the possibility of the S. D. figure recurring. It appears that if the circuit is so arranged that the instrument itself is not shunted across the 60-cycle leakage path, the S. D. figure will not show up; and work is being done in several directions to effect this change in the potentiometer coupling. From this standpoint it is felt that the layout at Station 172 was a particularly fortunate one, and contributed considerably to the study of lightning phenomena by means of the klydonograph. It has resulted in definitely disclosing a weakness in one type of potentiometer arrangement and has eliminated the possibility of misleading conclusions as a result of faulty data.

*Effect of Normal Line Potential on Recorded Voltages.* The surge recorder shows the maximum crest voltage at its terminals, and by the use of the potentiometer ratio, the crest voltage on the line, when potentiometer coupled to the circuit under investigation. It is, therefore, clear that a recorded surge must be the instantaneous sum of the surge voltage and the line voltage. In Fig. 16 are shown the instantaneous voltages of the three line wires of a 132-kv. circuit during one complete cycle.



CREST 80 K.V. OF LINE WIRES TO GROUND.

| DEGREES | 0 | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 | 270 | 300 | 330 | 360 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PHASE-1 | 0 | +54 | +93 | +108 | +93 | +54 | 0 | -54 | -93 | -108 | -93 | -54 | 0 |
| " 2 | -93 | -108 | -93 | -54 | 0 | +54 | +93 | +108 | +93 | +54 | 0 | -54 | -93 |
| " 3 | +93 | +54 | 0 | -54 | -93 | -108 | -93 | -54 | 0 | +54 | +93 | +108 | +93 |

Fig. 16—Instantaneous Voltage of 132-Kv., Three-Phase Line

Now assume a voltage surge of 300 kv. positive on all three line wires, and further, that this surge occurs at 210 deg. on the time scale. Due to normal line voltage No. 2 phase is 108 kv. above ground, and No. 1 and No. 3 phases 54 kv. below ground. Surge recorders at this location would indicate the sum of normal plus surge voltage; and conditions in Table II would obtain.

While 18 per cent error in surge recorder instruments, including line coupling in their present stage of develop-

TABLE II

| | Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|
| Surge voltage (kv.) | 300 | 300 | 300 |
| Line voltage (kv.) | 100 | −54 | −54 |
| Recorded voltage (kv.) | 400 | 246 | 246 |
| Per cent error | 33 | 18 | 18 |

ment, is perfectly reasonable, and 33 per cent may be slightly excessive, let us examine the ratio of recorded to actual voltages on phases 1 and 2. This ratio is 1.63 for the recorded voltage and 1.00 for the actual voltage, giving an error of 63 per cent, which is distinctly excessive if the data are to be used in studying surge voltage attenuation, effect of the ground wire, voltages on lightning arresters and the like.

It should be pointed out, however, that the effect of normal line voltage on surges decreases with increase of the surge magnitude. An error of 63 per cent with a 300-kv. superimposed surge becomes only 18 per cent for a 900-kv. surge. With surges of low magnitude the error becomes greater; and in some cases an erroneous conclusion may be reached unless the influence of normal line voltage is considered.

While the above feature is decidedly fundamental, it is felt that its importance in analyzing data should be emphasized at this time to forestall any wrong conclusions being drawn from data, particularly where surges of the lower magnitudes are involved.

## VIII. CONCLUSIONS

1. The choke coils reduced the recorded lightning voltage in the order of 25 per cent, although tests on this feature are not extensive enough to prove this statement conclusively. Reflections at the choke coil may also have had a decided effect in altering the incoming voltage wave, so that this 25 per cent may not have been an actual reduction of the initial wave.

2. The protective value of the ground wire could not be proved conclusively from the data, due largely to the presence of S. D. figures in the records. It is planned to continue this investigation the coming year.

3. The record on instruments at the time of line trip-outs due to lightning (maximum 5.0 times normal voltage is found) indicates that the voltages higher than recorded must have existed on the line for flashover to have occurred. This brings up the point that surge recorders must be placed in generous numbers on a line to study line performance thoroughly. A further tendency is indicated from these data, that is, that lightning voltages do not travel a great distance; otherwise there would have been recorded high voltages on some of the surge recorders.

4. The polarity of lightning surges indicated a preponderance of positive impulses. Of 96 surges 42 were positive, 25 negative, and 29 highly damped.

5. Transient voltages on the ground wire at the tower were recorded as high as 8200 volts negative during a lightning storm, and in all cases were of the order of 3000 to 4000 volts. These surges were recorded at times of lightning storms and switching; in some cases no cause could be found. This relatively low voltage on the ground wire compared with the higher voltage on the line is positive evidence of the effectiveness of the ground wire in reducing the impulse voltages on the line itself.

6. Lightning arrester discharges in all cases were of the general order of 200 to 400 amperes, although two cases were recorded as high as 1260 and 2620 amperes. Measured currents were in all cases the sum of the currents in all three legs of the arrester. The highest recorded current was negative; the 1260 ampere value was highly damped, being initially negative.

7. Attenuation of lightning surge voltages failed to give any conclusive results largely on account of the presence of S. D. figures.

8. The attempt to determine voltage changes at the termination of the ground wire was not very successful due largely to insufficient reliable data and the proximity of the test point to the substation where the numerous changes in surge impedance introduced the question of reflected waves.

9. Switching surges have been recorded as high as 5.2 times normal, which seems to be in general agreement with previous results. Over 50 per cent of the switching surges were of the order of two and one-half times normal to ground or higher. By isolating switching surges in four special tests, it was shown that the surge voltage on deenergizing the line was approximately twice as great as on energizing the line. Switching surges are mostly of a highly damped nature, as shown by the data.

10. No voltage was recorded between the base of a tower and ground, during the tests, although the voltage at the peak of the tower to which the ground wire was attached indicated surge voltages up to 8200 volts.

11. The relative lightning voltage on parallel conductors is shown to be equal, although the data are too limited to prove this point definitely.

12. It was shown that the two types of surge recorders are equally reliable from the point of view of measuring surges; but it was also shown that the type of coupling employed to connect the instruments to the line must be carefully studied and selected or erroneous conclusions may result. This point is clearly shown from the experience at Tower 172, Stations 20, 21, 22, and 23.

13. This investigation, it is believed, has resulted in some new information, some confirmatory and some negative. All this information is valuable, although a great deal more data must be obtained to properly solve the lightning problem. With this data, together with the data it is hoped to get during the year 1928 lightning season, it is believed some further light will be thrown on the lightning voltage situation.

Acknowledgment is due to the various men in the organization of the General Electric Company, the Westinghouse Electric Manufacturing Company, the American Gas and Electric Company, the Ohio Power Company, and Appalachian Electric Power Company, who participated and helped in the work of this investigation.

## Discussion

For discussion of this paper see page 1147.

# Surge Voltage Investigation on 220-Kv. System of
## Pennsylvania Power and Light Company

BY NICOLAS N. SMELOFF[1]

Associate. A. I. E. E.

***Synopsis.**—This paper presents the history of the operating experience and surge-voltage recorder data for the years 1926 and 1927, on the first 220-kv. line in the East.*

*The system of the Pennsylvania Power & Light Company is described. Lightning weather data, design characteristics of the 220-kv. line involved, and details of connection and installation of surge-voltage recorders are given.*

*The study shows the magnitude of surge voltages encountered, method of classification, effect of our overhead ground wires, etc., and points out the necessity for comprehensive lightning research, which will permit a systematic solution of transmission problems.*

* * * * *

### GENERAL

THE system of the Pennsylvania Power & Light Company is located in the northeastern part of Pennsylvania. It traverses several mountain ranges, which attain a maximum elevation of 2100 ft. In the anthracite coal fields and in the northern part of the system the terrain is particularly rugged, rocky, and exposed to storms.

Coal mining, cement, metallurgical, slate, textile, furniture, shoe, and other miscellaneous industries provide a field for a desirable, important, and diversified load. In addition to the above, a number of large communities depends entirely upon this system for electrical power. The natural growth of the system and favorable economic conditions permit the establishment of interconnections with practically all neighboring systems.

Power is generated in eight major steam stations. With one exception these stations use small sizes of anthracite—either pulverized or on stokers. In addition, one major hydroelectric station of 40,000-kw. capacity at Wallenpaupack furnishes power during peak load periods. This hydroelectric development, because of its design and method of operation, provides on short notice (90 to 120 sec.) a capacity which assists materially in the economical operation of the steam stations.

The present major network and primary distribution is operated at 66,000 volts. Over 50 per cent of this 66-kv. network is on wood pole lines. Numerous step-down transformer stations are connected directly to the main lines, thus affording readily accessible power to large, as well as comparatively small consumers at the system primary voltage.

This 66-kv. system, at present, is connected at Siegfried with the hydroelectric station at Wallenpaupack by means of a 220-kv. transmission line, which was placed in operation in 1926. Although it was the first line operating at this potential in the East, of far more importance is the fact that it was the first 220-kv. line in lightning infested territory, and for this reason it afforded the first substantial experience with an opportunity for study of the effects of lightning on a line and equipment insulated for 220-kv. operation.

During 1928, additional lines at 220-kv. were placed in operation establishing an interconnection between the systems of the Philadelphia Electric Company and the Pennsylvania Power & Light Company, and consequently tying together the two hydroelectric stations, Conowingo and Wallenpaupack. This connection is shown on the map of Fig. 1. Later these lines will be a part of an extensive 220-kv. network and interconnection between large stations of several systems.

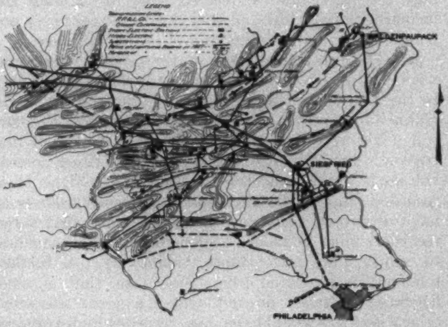


FIG. 1—MAP OF PENNSYLVANIA POWER & LIGHT CO. SYSTEM

Showing major transmission lines, power plants, substations, and the path and number of lightning storms for the season of 1927

### LIGHTNING WEATHER DATA

Lightning weather observations were made by the operating organization at numerous company substations. The data thus obtained were analyzed in conjunction with the U. S. Weather Bureau records.

The map (Fig. 1) indicates the principal mountain ranges and valleys and the paths of lightning storms during 1927. The solid lines denote the main general paths of the storms, while the broken lines indicate divergencies and show how storms break up and follow

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*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

different routes. In general, the storms seem to follow the mountain ranges rather closely, breaking through at points where streams have formed definite gaps. The general cyclonic storms moving eastward over the territory, extend from the northern to the southern edges of the system and during the course of their travel are reported from practically all stations. Of approximately 60 storms occurring during the 1927 season, 25 were of this wide-spread type, 26 were of a generally local type, following only one of the various paths indicated, while the remainder were entirely local, being reported from only one or two adjacent stations.

The duration of the storms is variable. The purely local storm may last from fifteen minutes to three hours, depending on conditions at the time it occurs. The general type of storm may be in evidence for a period ranging from two to seven hours before it has entirely disappeared from all parts of the system.

The map (Fig. 1) also shows, for the year 1927, the number of lightning storms reported from various locations. These data are not indicative of storm severity or duration and may or may not represent an average year. From this information it may be seen that the system under discussion is subjected to lightning storms in excess of the average over the country.[2] The records show that during 1927, 35 of the total of 59 storms observed caused line trip-outs, for the year 1926, 40, and for 1925, 51 storms caused trip-outs and were recorded. No complete record was kept of storms which did not affect operation during these earlier years.

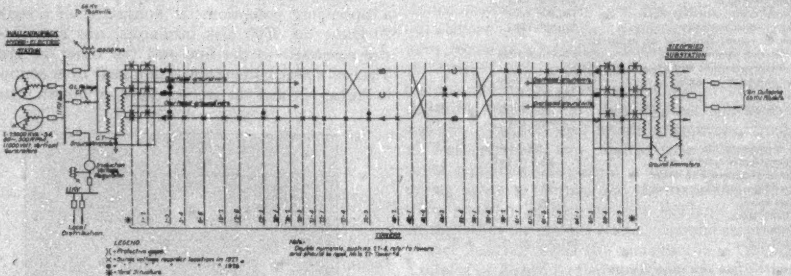

Fig. 2—One Line Diagram of Wallenpaupack-Siegfried 220-Kv. Line and Terminal Stations

Showing locations of surge-voltage recorders, transpositions, protective gaps, and overhead ground wires

## OBJECT OF SURGE VOLTAGE STUDY

The importance of successful operation of large transmission systems cannot be overemphasized, and the minimizing of the effects of voltage disturbances caused by flashovers due to lightning is of importance. In eastern territory lightning is a major and uncontrollable source of trouble and is the most complicated and least known phenomenon. As a result, the power industry has before it the big problem of lightning research—what lightning is, how to handle it, and how to apply this knowledge in obtaining better line performance.

The comprehensive collection of operating data, supported by data from surge voltage recorders, laboratory research, study, and correlation of facts will undoubtedly permit, within a few years, a systematic solution of transmission problems.

The surge voltage recorder is a big and important tool in lightning research in the field. It permits, with certain limitations, the study of lightning potentials, wave shape of impulses encountered on transmission lines, attenuation, effect of overhead ground wires, etc. It throws some light, also, on the little known phenomenon of the relation of lightning and power arcs.

Of course, the value of the data resulting from the study covered by this paper, obtained during a short period of time, should not be overestimated, and deductions so drawn cannot be considered as indisputable facts. On the other hand, the possibility of obtaining a mass of rather conflicting data at the outset should not discourage further studies, as its dependability will increase with the length of period observed, *i. e.*, with the number of lightning seasons.

## THE WALLENPAUPACK-SIEGFRIED LINE

The terrain crossed by the Wallenpaupack-Siegfried Line is mountainous, quite rugged, rocky, and timbered at its northern end where a maximum altitude of 2100 ft. is attained. Rolling farming country prevails at the southern end. When excavations for the tower footings were made, it was found that over a large portion of the line, the material removed consisted of broken or loose rock which was very difficult to drill or bore. The ground and tower footing resistance averages 50 ohms, with a maximum of 325 ohms on the mountain tops.

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[2] Overhead System Reference Book, N. E. L. A., p. 479, Table 122.

Table I gives the general characteristics of the line,[3] and Fig. 2 indicates the terminal connections. Table II contains pertinent information about the terminal apparatus, and Fig. 2 is the one line diagram. Fig. 3 shows the standard "A" type of tower. Fig. 4 shows the suspension insulator assembly with ring and horns.

During the summer of 1927 (May-July) two overhead ground wires were installed for the approximate distances of 20 miles at the Wallenpaupack (northern) end of the line and of five miles at the Siegfried (southern) end.

### SURGE VOLTAGE RECORDERS

The surge voltage recorder study was made cooperatively by the General Electric Company and the Pennsylvania Power & Light Company. The former furnished a number of surge voltage recorders which the latter installed and serviced throughout the seasons. The data from the instruments were analyzed, and were correlated with the system operator's log and weather reports.

TABLE I

GENERAL CHARACTERISTICS OF THE WALLENPAUPACK-SIEGFRIED LINE

| | |
|---|---|
| Frequency | 60 cycles |
| Voltage— | |
| Between phases | 220,000 volts |
| Phase to ground | 127,000 volts |
| Normal crest volts to ground | 180,000 volts |
| 60-cycle flashover (dry) | 600,000 volts |
| Line insulation flashover at lightning voltages, approximately | 1,800,000 volts |
| *Protective gaps at stations—flashover at lightning voltages | 1,300,000 volts |
| Circuits | 1 |
| Right-of-way | 100 ft. cleared and danger timber cut |
| Length | 65 mi. |
| Type of construction | Steel tower |
| Configuration of conductors | 22.5 ft. flat |
| Height of conductors at tower | 65.7 ft. |
| Height of ground wires at tower | 75.5 ft. |
| Average span | 1,100 ft. |
| Maximum span | 2,400 ft. |
| Conductor | 795,000 cm. A. C. S. R. |
| *Ground wire—two | 184,000 cm. A. C. S. R. |
| Insulators— | |
| Locke No. 7500 high strength unit: | |
| Suspension assembly | 14 units |
| Tension assembly | 16 units |
| Arc protection and grading | Rings at line end, horns at ground end. |
| Distance from grading ring to horn of suspension assembly | 5 ft. 11¼ in. |
| Transpositions | See Fig. 2 |
| Relays: | |
| Wallenpaupack | Overcurrent and ground |
| Siegfried | Overcurrent and reverse power |

*Installed in 1927.

The recorder used was the General Electric two-electrode instrument,[4] which makes possible the measurements of transients by positive Lichtenberg figures.

TABLE II

GENERAL CHARACTERISTICS OF SUBSTATION EQUIPMENT

| | |
|---|---|
| *Transformers*: | |
| At Siegfried | |
| Four single-phase units, bank capacity | 86,600 kv-a. |
| High voltage | 127,000/220,000 Y –<br>114,000/198,000 Y |
| Low voltage | 38,100/ 66,000 Y – |
| Tertiary | 10,750 Delta |
| Manufacturer | General Electric Co. |
| At Wallenpaupack: | |
| Four single-phase units, bank capacity | 50,000 kv-a. |
| High voltage | 134,000/231,000 Y –<br>121,000/209,000 Y |
| Low voltage | 11,000 Delta |
| Manufacturer | General Electric Co. |
| *220-Kv. Oil Circuit Breakers*: | |
| Wallenpaupack | None |
| Siegfried | None* |
| *Lightning Arresters*: | |
| Wallenpaupack | None |
| Siegfried | None |

NOTE. All switching of the energized line is done from 11 kv. and 66 kv. side of transformers at Wallenpaupack and Siegfried respectively. Neutral dead grounded at each transformer station.

*Three 220-kv. oil circuit breakers placed in service in 1928 with the advent of the Siegfried-Philadelphia 220-kv. line.

The instrument was connected to the line through a capacitance potentiometer consisting of a string of 20 Locke No. 7500 disk insulators, one end of which was connected to the line and the other to ground. The instrument potential was obtained by a connection to the cap of either the second, third, or fourth insulator from the grounded end of the string depending upon potentiometer ratio desired (see Tables III and IV).

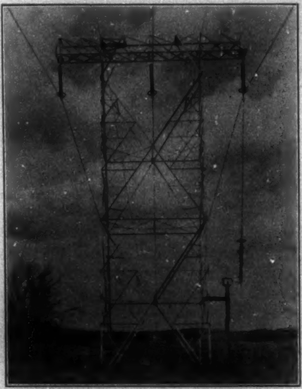

FIG. 3—TYPICAL SURGE-VOLTAGE RECORDER INSTALLATION

Type "A" tower potentiometer assembly and surge-voltage recorder installation

A typical surge voltage recorder installation is shown in Fig. 3. The recorder is installed on an elevated platform, which makes it inaccessible to unauthorized persons. Provision for grounding the instrument when it is serviced as well as other features are incorporated to make the installation safe. This arrangement of the recorder in its sheet metal housing results in a ratio of 60 to 1 between line voltage and instrument voltage for the 20-4 insulator combination, a ratio of 70 to 1 for the 20-3 insulator combination and 90 to 1 for the 20-2 insulator combination. These ratios were determined in the High Voltage Laboratory of the General Electric by calibrating an assembly similar to the field arrangement by impression of surge voltages of known magnitude and wave form. The operation of the surge voltage recorder was fully described before the Institute.[5]

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[3] "Wallenpaupack Hydro Electric Development," A. E. Silver and A. C. Clogher, *Electrical World*, July 24, 1926.

[4] *Measurements of Surge Voltages on Transmission Lines Due to Lightning*, by E. S. Lee and C. M. Foust, A. I. E. E. TRANS., Vol. XLVI, 1927, p. 339.

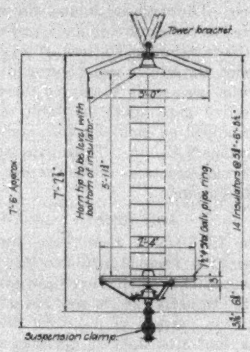

Fig. 4—Wallenpaupack-Siegfried 220-Kv. Line

Single string insulator assembly

The Lichtenberg figures recorded on the photographic films of the various instruments were interpreted as to magnitude, nature, and time of occurrence. Simultaneous registrations on several instruments located at different points along the line have been grouped together and designated as a single surge. The magnitude of the surge voltage on the instrument was determined by figure size, and the magnitude of the surge voltage on the conductor was obtained by multiplying the recorded instrument voltage by the potentiometer ratio. All surge values given in this paper refer to the voltage between the line conductor and ground.

## 220-Kv. Operation of Recorders During 1926

The 1926 study will be touched upon briefly to give a more complete perspective of the experience with the line under study.

During the 1926 season, the line was operated in two distinct periods, from April 23 to August 14 at 220 kv., and from August 15, 1926 to March 13, 1927, at 66 kv.

The locations of the instrument were so arranged as to obtain a maximum of data from the limited number of instruments. From Fig. 2 and Table III it may be seen that on phase *A* there were instruments at each end with three along the line at approximately equal intervals. Phase *B* was equipped with instruments only at each end. Table III also contains information on potentiometer ratios used.

During this period a number of severe lightning storms passed over or near the line. Before the installations of the instruments, five trip-outs were recorded, and after thirteen trip-outs. After all, except two apparatus trouble trip-outs, the line was returned to service at will after approximately one minute interval. Of these eighteen trip-outs, one was accidental, two were caused by apparatus troubles at Wallenpaupack, two resulted from flashovers between conductor and yard structural steel at Siegfried during lightning storms, and the remaining thirteen were probably caused by line insulator flashovers. At the end of the summer season, a careful examination of each insulator string (by climbing towers) disclosed a total of 24 flashed insulators strings. It was impossible to detect most of these flashed insulators from the ground on inspections made after each trip-out. The insulator flashovers resulted, in most cases, in a slight pitting of caps, rings, and horns, and burned and chipped spots on the porcelain, but in no case was an insulator damaged seriously.

On Fig. 5 is plotted the number of surges against surge magnitude. Of the total of 30 lightning surges recorded, 9 were 10 times normal. Switching resulted in 19 surge records with less than 3 times normal voltage. In addition, there was a total of 14 surges

TABLE III

LOCATION OF SURGE VOLTAGE RECORDERS AND DATES OF THEIR OPERATION

1926

| Station | Mile No. | Tower No. | Phase | Tower position | Potentiometer† | Date started | Potentiometer | Date started | Date stopped |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | 220-Kv. Operation | | 66-Kv. Operation | | |
| 1-3A | 1 | 3 | *A* | West | 20-4 | 7-20 | 7-1 | 8-15 | 10-31 |
| 1-3B | 1 | 3 | *B* | Middle | 20-4 | 7-20 | 7-1 | 8-15 | 10-31 |
| 17-1A | 17 | 1 | *A* | West | 20-4 | 7-20 | 7-1 | 9-26 | 10-31 |
| 32-3A | 32 | 3 | *A* | West | 20-4 | 7-20 | 9-2 | 8-26 | 10-31 |
| 48-3A | 48 | 3 | *A* | Middle | 20-4 | 7-19 | 9-2 | 8-27 | 10-31 |
| 65-5A | 65 | 5* | *A* | East | 20-4 | 7-24 | 9-2 | 8-23 | 10-31 |
| 65-5B | 65 | 5* | *B* | Middle | 20-4 | 7-24 | 9-2 | 8-23 | 10-31 |

*First tower from station.

†"20-4" denotes: 20 disk units between line and ground, with the recorder connected to the cap of the 4th unit from the ground end.

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Loc. cit. 5.

arising from unknown causes, having a maximum value of 1.5 times normal.

### 66-Kv. Operation of Recorders during 1926

The 66-kv. operation necessitated a change of insulator potentiometer ratio. Table III shows the changes made and the location of the instruments. In changing from the 220-kv. to 66-kv. operation, the line insulation was also changed from a 14-unit string to a 4-unit string by short-circuiting ten of the insulator units. This reduction of line insulation extended for distances of three miles from Wallenpaupack and of three miles from Seigfried. With the exception of the installations at tower 17-1, the line insulation at each surge recorder station and at one tower on either side was similarly reduced.

A total of three 66-kv. trip-outs was caused by lightning flashover of insulators at tower 1-2 at the Wallenpaupack end on which ten units had been short circuited. Surge voltages recorded showed that a maximum of ten times normal voltage occurred during these trip-outs. The records from the station at tower 17-1 showed, however, a voltage 29 times normal (based on 66-kv. line voltage), or 1560 kv. This appears to demonstrate that the insulation to ground is a factor in the determination of the maximum voltage to which surge voltages due to lightning may arise.

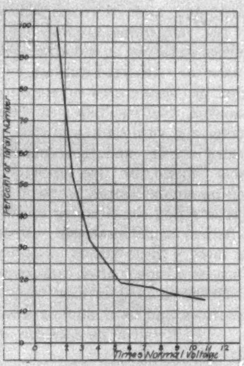

Fig. 5—Magnitude of Surge Voltages 1926

### Preventative and Protective Measures

To secure greater safety to the apparatus against lightning surges of dangerous magnitude, two protective measures were adopted during the spring of 1927:

1. The installation, immediately adjacent to the terminal stations, of lightning protective or spillway gaps of approximately 1300-kv. impulse flashover, and
2. The installation, for distances of approximately five miles, at each end of the line of two overhead ground wires.

For the purpose of studying the effects of overhead ground wires and to further reduce the insulator flashovers, an additional 15-mi. section at the Wallenpaupack end of the line was equipped with these ground wires. Thus the line was protected by ground wires for 20 miles at the Wallenpaupack end, and for five miles at the Siegfried end, leaving the middle section of 40 mi. unprotected. (See Fig. 2). The 20-mile section contains the highest in point of altitude, and in 1926 more than 50 per cent of insulator flashovers occurred on this part of the line. The overhead ground wire was metallically connected to the station grounds, and at the ends away from the transformer stations, it was also effectively grounded through a nest of ground rods. No special provision was made to ground the tower legs.

The protective gaps took the form of insulator assemblies equipped at each end with standard rings having separation of 42.5 in. These gaps were located on the transformer structures and on the first suspension towers at both stations.

### 1927 Study

During the 1927 season there were three distinct periods of operation: From March 13 to May 27, the line was operated at 220 kv. without overhead ground wires; from May 27 to July 25 it was deenergized and grounded for the purpose of installing the overhead ground wires; and after July 25 operated at 220 kv. with two overhead ground wires as described.

*Location of Recorders.* By the close of the season, a

TABLE IV
LOCATION OF SURGE VOLTAGE RECORDERS AND DATES OF THEIR OPERATION
1927

| Station | Mile No. | Tower No. | Phase | Tower position | Potentiometers† | Date started | Date stopped |
|---|---|---|---|---|---|---|---|
| Wallenpaupack Bus | | | *A* | | 20–3 | 7–26 | |
| 1–3A | 1 | 3 | *A* | West | 20–3 | 3–12 | 11–2 |
| 1–3B | 1 | 3 | *B* | Middle | 20–3 | 3–12 | 11–2 |
| 1–3C | 1 | 3 | *C* | East | 20–3 | 4–9 | 11–2 |
| 3–4A | 3 | 4 | *A* | West | 20–3 | 7–19 | 11–2 |
| 6–5A | 6 | 5 | *A* | West | 20–3 | 7–19 | 11–2 |
| 10–2A | 10 | 2 | *A* | West | 20–3 | 7–19 | 11–2 |
| 12–6A | 12 | 6 | *A* | West | 20–3 | 7–19 | 11–2 |
| 17–1A | 17 | 1 | *A* | West | 20–3 | 4–16 | 11–2 |
| 20–1A | 20 | 1 | *A* | West | 20–3 | 7–19 | 11–2 |
| 20–3A | 20 | 3 | *A* | West | 20–3 | 7–19 | 11–2 |
| 21–4A | 21 | 4 | *A* | West | 20–3 | 7–19 | 11–2 |
| 22–1A | 22 | 1 | *A* | West | 20–2 | 7–25 | 11–2 |
| 27–4A | 27 | 4 | *A* | West | 20–2 | 7–26 | 11–2 |
| 32–3A | 32 | 3 | *A* | West | 20–2 | 4–29 | 11–2 |
| 40–2A | 40 | 2 | *A* | West | 20–2 | 7–26 | 11–2 |
| 48–3A | 48 | 3 | *A* | Middle | 20–2 | 4–29 | 11–2 |
| 52–4A | 52 | 4 | *A* | Middle | 20–2 | 7–24 | 11–2 |
| 56–2A | 56 | 2 | *A* | East | 20–2 | 7–24 | 11–2 |
| 61–1A | 61 | 1 | *A* | East | 20–3 | 7–24 | 11–2 |
| 61–3A | 61 | 3 | *A* | East | 20–3 | 7–24 | 11–2 |
| 62–4A | 62 | 4 | *A* | East | 20–3 | 7–24 | 11–2 |
| 64–1A | 64 | 1 | *A* | East | 20–3 | 7–24 | 11–2 |
| 65–5A | 65* | 5 | *A* | East | 20–3 | 3–13 | 10–31 |
| 65–5B | 65 | 5 | *B* | Middle | 20–3 | 3–13 | 10–31 |
| 65–5C | 65 | 5 | *C* | West | 20–3 | 3–29 | 10–31 |

*First tower from station.

†"20–3" denotes: 20 disk units between line and ground, with the recorder connected to the cap of the 3rd unit from the ground end.

total of 34 instruments was connected to the line as shown on diagram, Fig. 2, and Table IV. Of this number, 26 were coupled to the line through insulator string potentiometers, and 8 were coupled through two special capacitance transformer bushings. These bushings were located on phase *A* near each transformer station. Both bushings were installed after the close of the lightning season and are not shown on Fig. 2 or Table IV.

Table IV shows the potentiometer ratios used.

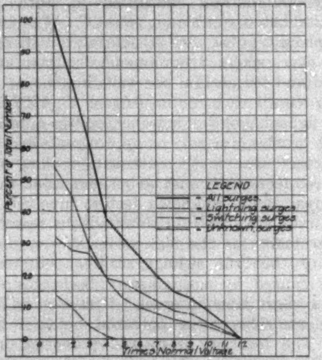

Fig. 6—Surge Classified by Origin 1927

*Nature of Surge Voltages.* The Lichtenberg figures recorded were classified according to their character, namely, Type I, II, and III,[6] *i. e.*, very slow, medium, and very abrupt. As practically all of the surges were of Type II, these were further classified as highly damped (HD) and slightly damped (SD).

TABLE V
ORIGIN OF SURGE VOLTAGES
1927

| Origin | Number | Highest crest value | |
|---|---|---|---|
| | | Times normal | Kv. |
| Lightning | 48 | 11.7 | 2100 |
| Switching | 21 | 4.0 | 720 |
| From unknown causes | | 7.0 | 1260 |
| (a) HD | 29 | 4.9 | 880 |
| (b) SD | 51 | 11.7 | 2100 |
| Total | 149 | .. | .. |

The "highly damped" figures are interpreted as being produced by a surge voltage which lasts for only a few reversals of polarity, such as less than five. The "slightly damped" figures are of uncertain origin. They appear to be formed through the continuous application of alternating potentials for the duration of several seconds (long enough to produce film fog). During the period the line was grounded and deenergized no SD figures were recorded. In this period, however, HD figures were quite frequently recorded during lightning storms. This tends to indicate that the normal line excitation is required to produce SD figures.

During the 1927 investigation a total of 149 surges was recorded, ranging in magnitude from 1 to 11.6 times normal (180 kv. to 2100 kv.).

Correlation of the surges with weather and operating data indicated that many of the disturbances had been produced by lightning or switching. Others are of uncertain origin and have been classified as "from unknown causes." Table V and Fig. 6 show the number and maximum voltage of surges classified according to origin.

*Lightning Surges.* Fig. 7 shows that 56 per cent of the lightning surges exceeded five times normal. The classification as to polarity shows that there are comparatively few unidirectional surge voltages, although their magnitude may be quite high. The majority of lightning surge voltages on this system were oscillatory, with no definite tendency for either the positive or negative wave to be higher.

While the size of figures obtained is indicative of crest voltage values and some information relative to the rate of voltage rise may be obtained from figures characteristics, it is not possible to determine other factors such as relative shape and duration.

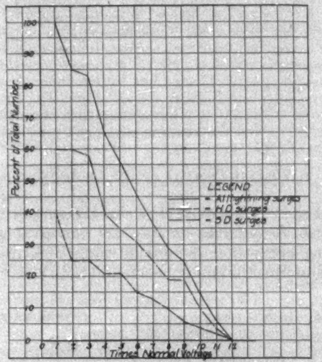

Fig. 7—Lightning Surges 1927

The curves of Fig. 7 show the relation between number and magnitude of surge voltages recorded. On Table VI it may be seen that all unidirectional voltages recorded have HD characteristics. Negative polarity prevails in the HD oscillatory surge voltages 9 out of 13 cases. The SD figures, however, show only two of the negative polarity out of a total of 30. The HD

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[6] K. B. McEachron, *Measurements of Transients by Lichtenberg Figures*, A. I. E. E. Trans., Vol. XLV, 1926, p. 712.

TABLE VI

POLARITY OF HD AND SD SURGE VOLTAGES PRODUCED BY LIGHTNING

1927

| Polarity | Number | Highest crest value<br>Times normal |
|---|---|---|
| (a) Unidirectional | | |
| HD Positive | 2 | 10 |
| HD Negative | 3 | 1.9 |
| SD Positive | 0 | 0 |
| SD Negative | 0 | 0 |
| (b) Oscillatory | | |
| HD: | | |
| 1. H. C. V. *Positive | 4 | 8.6 |
| 2. H. C. V. Negative | 9 | 10.0 |
| 3. H. C. V. Positive and Negative equal | 0 | 0 |
| SD: | | |
| 1. H. C. V. Positive | 7 | 11.7 |
| 2. H. C. V. Negative | 2 | 11.6 |
| 3. H. C. V. Positive and Negative equal | 21 | 11.6 |

*H. C. V.—Highest crest value.

figures in no case show equal magnitude of positive and negative voltages, whereas 20 out of the 30 oscillatory SD surge voltages are of equal positive and negative value.

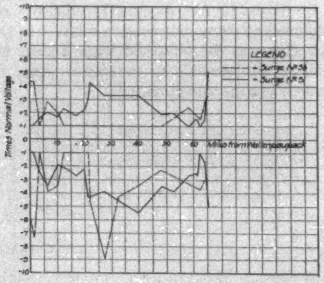

FIG. 8—VOLTAGE PROFILES OF HD LIGHTNING SURGES

TABLE VII

COMPARISON OF SURGE VOLTAGES RECORDED AS TO THE POSITION ON THE TOWER

1927

| Phases | Highest crest value times normal<br>A | <br>B | <br>C |
|---|---|---|---|
| At Wallenpaupack—Tower 1-3 | | | |
| Average voltage | 5.7 | 7.0 | 5.4 |
| Maximum voltage | 7.4 | 7.0 | 9.3 |
| At Siegfried—Tower 65-5 | | | |
| Average voltage | 4.8 | 5.4 | 3.4 |
| Maximum voltage | 7.4 | 11.6 | 4.8 |

Fig. 8 shows the profiles of typical HD surge voltages. Surge No. 38 occurred on July 26 during a general lightning storm after the ground wires were installed. The transformer oil circuit breakers at both ends tripped with ground current indication at both stations. Relays indicated trouble on phase *C*. The protective gap on phase *C* at the yard structure at Wallenpaupack flashed over, where a number of insulator units was blistered and the shell of one unit broken.

Surge No. 51 occurred on August 13, 1927, during a general lightning storm; however, no trip-outs followed.

These profiles give only an approximate and possibly an incorrect idea of the attenuation along the line. In this connection, it must be borne in mind that there are a great many unknown factors involved. While these curves are based on simultaneous recordings on the instruments as the film moves slowly, there is a possibility that the voltage readings obtained were actually caused by a number of discharges occurring within a short time interval. Further, the recorder actually measures surge potential between line and tower. The location of neutral potential or "good ground" is uncertain. In dealing with surge voltages of very steep wave front, ground resistances, although low, may be effective in determining potentials between line and tower. The position and extent of cloud charge is also unknown.

Due to the short period of operation with the overhead ground wires, it would be premature to draw definite quantitative conclusions.

The comparison of voltages recorded relative to the position on the tower is not definite enough to permit drawing conclusions (Table VII).

During the 1927 season, the line tripped out eight times. One trip-out was caused by an accidental ground on the 66-kv. bus at Siegfried and produced only a small switching surge. The remaining seven trip-outs occurred during lightning storms but only

TABLE VIII

TRIP-OUTS DURING LIGHTNING STORMS

1927

| No. | Date and time of trip-outs | Description of failure | Tower | Highest Crest Voltage<br>Times normal | <br>Station | Nature of surge voltage |
|---|---|---|---|---|---|---|
| 1 | 4-21-27, 8:06 P. M. | Ten unit string on *A* and *B* phases flashed | 1-2 | − 9.3<br>+ 5.3 | 1-3A | SD Oscillatory |
| 2 | 4-21-27, 11:05 P. M. | Same as No. 1 | 1-2<br>65-4 | + 10.0<br>+ 1.0 | 1-3B<br>65-5C | HD Positive |
| 3 | 5-10-27, 5:26 P. M. | *B* and *C* phases flashed | 1-2 | + 2.3<br>− 8.6 | 1-3B | HD Oscillatory |
| 4 | 5-10-27, 5:28 P. M. | Same as No. 3 | 1-2 | Not recorded | .. | .. |
| 5 | 7-26-27, 5:09 P. M. | Protective Gap at Wallenpaupack on Phase *C* flashed | 1-0 | − 9.3 | 1-3*C* | HD Oscillatory |
| 6 | 7-26-27, 5:14 P. M. | Same as No. 5 | 1-0 | Not recorded | .. | .. |
| 7 | 7-27-27, 3:55 P. M. | Location unknown | .. | + 5.3<br>− 5.3 | 48-3A | HD Oscillatory |

five surges are directly correlated to respective trip-outs. Due to the very short intervals (2 and 5 min.) between two trip-outs at two different times and due to the slow movement of the film, the surge record on the film registered only one surge each time. Table VIII gives the surge voltages correlated as to trip-outs and location of failures.

*Surges Due to Switching Operations.* Twenty-one surges which coincided with normal switching operations were recorded. Frequently switching produced no records on the surge voltage instruments. This fact is probably due to the low tension switching. The majority of switching operations which produced records were those caused by energizing the line. The maximum value recorded at any time was 4.0 times normal and all were of the HD nature. Most of the switching surges were recorded simultaneously at several stations, although never at all stations.

*Unknown Surges.* Some of the surges of unknown origin are thought to have been caused by lightning storms not observed by station operators.

### CONCLUSIONS

1. During the investigations of 1926 and 1927 surge voltages of a magnitude of 2100 kv. were recorded during lightning storms.
2. The majority of surge voltages due to lightning were oscillatory, although a few HD unidirectional surge voltages were recorded.
3. The highest voltages recorded check fairly well with the prediction made from results of insulator calibration in the laboratory.
4. The line insulation apparently limited the magnitude of lightning surge voltages.
5. Not all of the maximum lightning surge voltages caused power arcs.
6. No definite or reliable information was obtained on attenuation.
7. The quantitative value of protection afforded by the overhead ground wire cannot be deduced from the limited data.
8. The highest surge voltages correlated to switching was four times normal (720 kv.), with practically all surges produced by energizing the line. All such voltages were of the HD nature.
9. Many surge voltages were recorded with no possibility of assigning a definite cause to them. These voltages reached an extreme magnitude of 11.6 times normal (2100 kv.).

### FUTURE STUDY

The surge voltage recorder study is being continued in 1928 and it is expected that more data will be obtained than in previous years. The 220-kv. switching also may furnish some valuable and interesting information. Furthermore, with the assistance of laboratory research, it may be possible to determine the relation and condition under which a lightning flashover will be followed by a power arc. This information is of importance in designing lightning proof lines.

Acknowledgment is made to Messrs. C. M. Foust, A. L. Price, F. B. Menger, and W. R. Kleckner for analyzing and correlating the surge voltage data, and to Messrs. A. E. Silver, W. W. Lewis, E. S. Lee, W. E. Lloyd, Jr., and C. A. Jordan for directing the study and criticizing this paper.

## Discussion

### PAPERS ON SURGE-VOLTAGE INVESTIGATION

(LEWIS, DILLARD, HEMSTREET AND EATON, SPORN, SMELOFF)

DENVER, COLO., JUNE 26, 1928

**J. F. Peters:** The authors mentioned three types of potentiometers used for this purpose. Mr. Sporn draws some valuable deductions from his experience with two types. Mr. Smeloff refers to the third form, the high-capacitance transformer bushing, in connection with his work during 1927. During one of our voltage investigations we used a condenser-type bushing with a tap brought out from the next-to-bottom condenser layer as a potentiometer. The results were entirely unsatisfactory. Due to the high capacitance of the bushing the disturbances for the duration were greatly modified in magnitude as indicated by direct comparison with the results from a ring-type potentiometer in the same station, and I would therefore suggest that in making connections to the line, care be taken not to get too high a capacitance in the potentiometer.

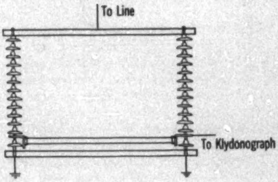

FIG. 1

**J. H. Cox:** The papers presented here are particularly gratifying to the writer, as they add additional weight to most of the conclusions, on the same subject, presented by him, in coauthorship with Messrs. McAuley and Huggins, before this Institute at the Midwinter Convention in 1927.[1]

Mr. Sporn has made an important contribution on the matter of potentiometers. In measuring surge voltages on high-voltage lines, a potentiometer is necessary. Theoretically, either a pure resistance or a pure capacitance is satisfactory. Practically, a resistance is not satisfactory where it must withstand sustained line voltage, and also, for high voltages its physical dimensions become so large that its physical capacity disturbs the voltage distribution. Therefore, the capacity potentiometer is the only one available, and the capacities should be so arranged as to eliminate the effect of any resistance path.

Mr. Sporn has discussed the effects of the leakage path in the insulator-string potentiometer. In another test, with which the writer was connected, pipe-type potentiometers were used but different conditions permitted the desired ratio with the use of only two pipes in the lower group instead of three as shown in Mr. Sporn's paper. The potentiometer used is shown in Fig. 1 herewith. It will be noticed that the klydonograph is tapped across the leakage paths of the two supporting insulator strings.

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[1] *Klydonograph Surge Investigations*, by Cox, McAuley, and Huggins, A. I. E. E. TRANS., Vol. XLVI, 1927, p. 315.

It was hoped that the capacity of the pipes would be large enough to predominate over the leakage coupling under all conditions. However, it was found that during rainstorms slightly damped figures, of the same nature as those produced by the insulator string potentiometer, were recorded. This was on a grounded neutral system where sustained oscillatory surges had never been recorded in two years' tests with ring-type potentiometers. This undesirable feature was eliminated by short-circuiting the leakage path about the klydonograph in the manner shown in the accompanying Fig. 2.

The pipe-type potentiometer was designed to provide a form more convenient than the ring-type from an installation point of view. The parts are easily provided. Fig. 3 herewith shows a form of pipe-type potentiometer which has recently been devised, which eliminates entirely the leakage path from the klydonograph circuit, and which is even more convenient to install than that shown in Fig. 2.

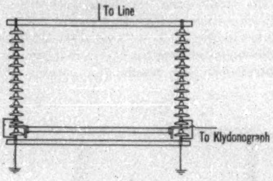

FIG. 2

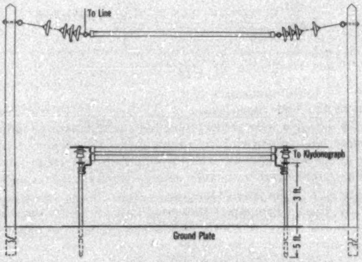

FIG. 3

The writer heartily agrees with Mr. Sporn in his decision to omit all S. D. (slightly damped) figures in his discussion of results. The evidence is quite conclusive that these figures were the result of a change in the ratio of the particular potentiometer used, under certain conditions, and to include them in data on which conclusions are based is misleading. With the exception of the S. D. figures, probably the data furnished with an insulator-string potentiometer are sufficiently accurate. However, the principal object of klydonograph tests is the recording of lightning voltages. These S. D. figures occur during rainstorms which usually accompany lightning. Figures occurring at this time, of course, obscure the legitimate figures recorded by voltages actually existing on the line. Therefore, with the elimination of the S. D. figures some of the most desired data are automatically eliminated. Hence, although the cheapness of the insulator-string potentiometer makes it particularly attractive, the writer does not feel that its use is justified.

**F. C. Hanker:** The need for more accurate information on the fundamentals of lightning phenomena has long been recognized, but no reliable recording device was available until the development and introduction of the klydonograph by Mr. Peters in 1923 made possible for the first time, the measurement of lightning and other surge voltages with a reasonable degree of accuracy. The characteristic which makes this device of particular value for the work, is that while it will operate for a week or more without attention, it will record the magnitude and polarity of voltages, the duration of which may be less than a microsecond and which may occur at any time.

It is desirable to obtain more complete information on surges caused on transmission lines than it is possible to obtain with the klydonograph. We secure reasonably accurate information on the magnitude within the limits of line insulation but in order to develop remedial devices more completely, it is important to establish other characteristics such as shape of wave front, duration, shape of wave tail, polarity, and effect of location of the stroke.

The Westinghouse Company, in cooperation with the Aluminum Company of America, is starting a lightning investigation in Tennessee using the form of cathode-ray oscillograph which was announced by Dr. Nordinder in his papers presented before the Franklin Institute and at the 1928 Winter Convention of this Institute.[2] In both of these presentations, he has given records of actual surge voltages recorded on an operating transmission circuit. This instrument, with other accessories used in the investigation, will yield all the information which has been lacking from the extensive klydonograph surveys that have been made during the past two years.

Due to the uncertainty of the occurrence of lightning, the complete story cannot be obtained in a short time. Existing circuits have limitations in dielectric strength that make it impossible to establish definitely the maximum voltages that are impressed on the circuit. It is expected that oscillograms obtained with the instrument now in operation will give sufficient data to permit establishing the complete wave form with a reasonable degree of accuracy and will point the way toward future procedure in obtaining the complete answer to the problem.

**L. L. Perry:** The papers show that on well designed transmission lines surges as high as ten or twelve times normal voltage must be expected in lightning country.

With regard to these conditions, I should like to ask Mr. Lewis these questions:

1. Would further developments in choke coils materially reduce the voltages reaching the arresters? Possibly it might increase.
2. To what percentage of normal voltage will a modern arrester limit the surge?
3. Does he recommend eliminating the arrester and making circuit breakers and transformers so that their insulation will withstand ten or twelve times normal without flashover or failure?

I should also like to ask him if he can supplement Table IV by the average height of conductor for line H-8?

I should also like to ask Mr. Foust from the operating records what percentage of trip-outs on one circuit involve the second circuit?

**A. C. Austin:** It is interesting to note that some of the conclusions drawn through a study of the performance of the insulator are apparently corroborated by the recent studies. Some years ago it was evident that where a line was under-insulated or had a number of faulty insulators, switching surges of appreciable magnitude apparently traversed the whole line, whereas lightning was localized. This was evident from the fact that a line might pass through a number of severe electrical storms before tripping out. In trying to energize the line again, however, it was sometimes necessary to avoid all switching surges and build up the voltage before the line would stay in. The conclusions reached were that the much higher disturbances produced by lightning were localized so that they did not affect a faulty insulator which was readily picked out by the lower voltage surge occasioned by switching, but which affected practically the whole line.

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[2] *The Cathode Oscillograph as Used in the Study of Lightning and Other Surges on Transmission Lines*, A. I. E. E. Quarterly TRANS., Vol. 47, April 1928, p. 446.

The need of more exact information as to the wave front or exact history of the disturbance on the line is still apparent. Tests in the laboratory indicate that many flashovers may take place at from 50 per cent to 60 per cent of the crest value occurring on the tail of the wave. The cathode-ray oscillograph shows that the flashover of an insulator may take place under a variety of conditions, depending upon the magnitude and duration of the wave. Both line troubles as well as tests in the high-voltage laboratory indicate that not only will the wave front produced by lightning vary considerably, but that the wave front for a single discharge is likely to vary over a very wide range.

To obtain records on the transmission line for actual conditions is not an easy problem, for a record which will cover a period of from 10 to 50 microseconds may not give the information on certain parts of the wave or voltage rise in sufficient detail. While apparently perfect oscillograph records may be obtained, it is necessary that these records are of the condition set up on the line by lightning and not a record of a disturbance set up in or greatly modified by the leads or coupling to the transmission line.

Tests made during the past year go to show that potentials above 800 kv. peak drop very rapidly and are usually attended by an oscillation during the decay of the charge. In most cases the discharge does not develop to the point where a power arc will follow until 10 or 15 microseconds after the crest is reached, the actual flashover taking place at a voltage of not more than 50 or 60 per cent of the crest voltage. From this it would appear that any scheme which will increase the time lag of the insulator or increase the attenuation will result in lower flashovers. On the other hand, tower or insulator construction or the attachment of electrodes which will reduce the time lag will result in increasing the number of flashovers.

The steepest wave fronts, although reaching very high values, may not cause as many flashovers as wave fronts at very much less slope and magnitude. This is particularly true where the dissipation or absorption of the charge is high.

**Philip Sporn:** Mr. Lewis's statement that the voltage on a line is limited by the flashover strength of the line insulators, ought to be modified, I think, to include not only the insulators but the structure itself, which, in turn, of course, includes the connection to ground. Mr. Peek has shown that the flashover value of a string of insulators increases with the amount of resistance to ground in series with that string and it is very important that in all discussions this be kept to the forefront as on no other basis have we been able to date to explain many phenomena that are clearly explained this way.

As regards the attenuation and the formula presented by Mr. Lewis, this is a fine attempt to get attenuation down on a mathematical basis but I do not believe that sufficient data have been gathered together for anybody to be able to say definitely that this is an exact and proved relationship. Some of the data that we obtained on investigations not mentioned in our paper would seem to indicate a much higher attenuation on lightning surges than the one given in the equation developed by Messrs. Foust and Menger. It is to be hoped that the work which is being carried on this year will give us more data on the subject.

**C. M. Faust:** Having been closely identified with the analyzing of the films from the surge recorders, I thought it might be somewhat interesting to try to explain and amplify and clarify possibly our methods of attack. For that purpose I have prepared a little chart. All surges were subject to two classifications, one with reference to nature or polarity characteristic and the other with regard to wave front. This chart may serve to explain these classifications.

All surges—Nature of Polarity Characteristic
- Unidirectional
  - Positive polarity
  - Negative polarity
- Oscillatory
  - Highly damped
    - (Predominantly pos.)
    - (Predominantly neg.)
  - Medium damped
  - Slightly damped

All surges—Type
- I. Slow wave front
- II. Medium wave front
- III. Fast wave front

Now with regard to this sort of classification and with particular reference to unidirectional or highly damped surges, there are two cases of field registration of interest.

1. Surges measured at only one station.
2. Surges measured at several stations.

Under the first case, a surge was readily classified with reference to the above chart. With regard to the second case, however, there were instances wherein station records disagreed, for example, indicated unidirectional at one station and oscillation but highly damped at others. With regard to the general classification of such a surge, two methods were followed:

1. Surge classified as oscillatory when registered as oscillatory at any one station.
2. Surge classified as to nature with regard to the polarity characteristic at the station where highest voltage registration was obtained.

The second classification appears to have particular advantage if the polarity of the induced charges is of interest. First, because reflection conditions may complicate the record at remote stations and secondly, because the switching surge due to the automatic trip-out cannot be separated from the lightning surge itself.

As both the above methods of classification have been used by the authors in preparing their papers, comparison of results must be performed with this in mind.

**J. F. Foote:** The formula for the attenuation of surges is probably of correct form for surges of a particular range of frequency. The results showing wide extent of M. D. surges and equally extensive H. D. switching surges would indicate that some other factors than voltage and line constants may affect attenuation. Would not further investigation of the possible effect of varying wave fronts probably show that the formula should include a wave front term or factor?

In stating that we may expect small trouble from M. D. surges because they are usually of less value than the impulse flashover of insulators, should we not recall that the M. D. surge may not be similar to the impulse wave upon which the insulator flashover value is based? It would seem reasonable to expect the flashover value of the insulator under the stress of such waves to be intermediate between the value obtained with an extremely steep wave front and that obtained at 60 cycles. In other words, the flashover value may be anywhere within the range of, say, three times to ten times the normal voltage, depending on the frequency of the surge. Thus if M. D. surges of moderately high frequency be encountered it is conceivable that flashovers may occur even at moderate amplitudes.

The conclusions regarding the effectiveness of choke coils do not seem entirely justified by the data given. That is, if it is meant that the amplitude of the voltage surge continuing beyond the choke coil tends to be in the order of 25 per cent less than the surge would be if the coil were omitted, the method of measurement used is inconclusive, since the voltage measured on the line side of the choke coil is not the voltage of the impressed surge, but this voltage increased by the partial reflection of this wave by the coil.

A choke coil is not a unidirectional valve nor is it more than a partial reflecting agent. Part of the impressed wave is probably reflected and the remainder passes through the coil. Should the transmitted surge then encounter another reflecting agent, as it usually will, in the way of a transformer winding or open switch, full or partial reflection of this wave will occur. If the distance between the choke coil and the second reflecting agent be short, attenuation will be small and the surge will strike the choke coil from the rear, as it were, being again partially reflected. Thus it is very possible that oscillations may build up in the short section beyond the choke coil, producing voltages in excess of the original surge.

The data in Mr. Sporn's paper indicate that in four out of ten cases this voltage did build up to greater values than even that of the partially reflected surge outside the coil. The other six show lower voltages beyond the coil than the reflected voltage in front of the coil, but it is not shown what the unreflected voltage might have been, and possibly the reduction was not a reduction in fact.

For many years the lightning-arrester engineers have regarded the choke coil as an accessory to assist in quick and certain gap break-down. However, the arrester is usually purchased to protect station, not line equipment, and to isolate such equipment from the arrester by the choke coil seems illogical in view of the considerations noted above.

**Fred O. McMillan:** It is interesting to note in Mr. Lewis' paper that the only points that are at any considerable distance from the drawn curve of Fig. 10 are those for surges 38 and 40, which were on the Pennsylvania Power and Light Company's system. Since this company's line has design constants different from the New England Power Company's line, it is to be expected that the constant $k$ for equations (1) and (2) would be quite different for these two surges.

I should like to ask Mr. Lewis to explain more fully why the voltages on the ground wire and tower were comparatively low. One would expect that in the case of very steep wave fronts the voltage rise would be very high until the reflected wave from ground wipes out the initial wave. It would appear that the only explanation of the low ground-wire voltages found must be in having waves of relatively sloping wave fronts.

**Harold Michener:** The Vincent 220,000-volt line was built without a ground wire. The southern half of it has been in operation for nearly two years and the complete line since last November.

Two months ago we had about six flashovers from lightning. We decided to put on two ground wires. We were careful, however, to tell our management that we didn't expect the ground wires to stop all the trouble from lightning.

The observations made at the time were rather interesting. Some of our men were working on a road near the location of the trouble and they reported that they could see streamers of fire, corona streamers, of some considerable length extending from the wires before the flashover occurred. The storm went on across that section of the old Big Creek lines immediately north of Vestal substation and caused no trouble on them.

This was pointed out as showing the value of the ground wire under the supposition that the two parallel old Big Creek lines were each equipped with one ground wire in this section and that the Vincent line was not. However, this proved to be the section in which there is about a 20-mi. gap in the ground wire on one of the old Big Creek lines. What we really had was the Vincent line in trouble from lightning, the storm passing on across the old Big Creek lines with lightning striking near on both sides of them and causing only fluctuations in the meters at Vestal even though one of them did not have a ground wire in this section.

Another thing of interest in that section of the old Big Creek lines through the San Joaquin Valley is that the only case of lightning trouble we have had there was on a tower equipped with two ground wires.

These facts, as we see them, only go to show that we cannot place too much dependence on the ground wires, and the fact that we are putting ground wires on the Vincent lines since we had the trouble with lightning shows we believe they will be of some benefit.

I rather expected to find more unanimity of opinion in regard to ground wires. I had gained the impression during the last two or three years that almost everyone was swinging to the belief that ground wires are a real protection. I think they are, but still there are things that seem a little doubtful about it.

**E. S. Fields:** The Union Gas and Electric Company of Cincinnati has been experimenting with a device for interrupting the flashover current before the protective relays operate to cause a trip-out of the transmission circuit with which some of you are probably familiar. Fig. 4 herewith shows the device in the present stage of its development for 66-kv. construction. A standard grading ring is installed at the conductor at the bottom of the insulator string. At the top of the string two 33-kv. expulsion fuses are installed in the position of arcing horns.

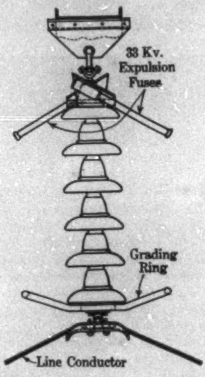

FIG. 4

In order to insure that the flashovers will take place from the end of the fused horn to the grading ring, the length and position of the fused horns and the dimensions of the grading ring have been determined from experiments conducted in the high-voltage laboratory with the impulse generator.

When a flashover occurs it strikes from the tip of the fuse to the grading ring. The power current that follows is interrupted by the operation of the expulsion fuse, usually in the first half cycle.

Sixty miles of 66-kv. line were equipped with this device in 1926 and the performance of this initial installation has led to the installation of the device on fifty miles of additional 66-kv. circuit this year.

During the summer of 1926, 77 per cent of the flashovers occurring on the original 60 mi. of 66-kv. line were interrupted by the fuses without service interruptions on the circuit. So far only 66-kv. circuits have been equipped with this device.

**A. O. Austin:** Both Mr. Smeloff and Mr. Michener made very interesting statements in connection with the use of the ground wire. Mr. Foote also mentioned the danger from flashover for voltages much lower than the crest voltages induced by lightning. It is these lower voltage flashovers which offer the most serious problem for the very long high-voltage transmission line.

It is interesting to note that the recent klydonograph records as well as tests in the laboratory go to show that the attenuation or dissipation of the charge is very rapid at the higher voltages, but that the attenuation drops off very quickly as the voltage is reduced. By applying this information to the operation of the line we are able to explain some of the apparently contradictory performance of the ground wire.

The ground wire functions primarily through its absorbing electrostatic capacity which tends to keep down the rise in potential for a given charge on the power conductor. While the presence of the ground wire reduces the quantity of the charge, on the power conductor, this is comparatively small where the separation of the conductors is large. Where no ground wire is used, a very high induced voltage or one above three-quarters of a million to one million volts is dissipated very rapidly as corona loss. If in the same installation a ground wire were installed such that the induced voltage on the power conductor would not rise above three-quarters of a million volts below which the corona loss is relatively small, it naturally follows that there would be more energy to set up a surge or traveling wave, which would have greater amplitude at a distance than where a large part of the energy was dissipated. In view of this, the increasing use of low-resistance ground wires must be watched very carefully as their use is likely to have the same effect upon the transmission line as the use of more limber springs and balloon tires had upon the automobile. While balloon tires and more limber springs greatly reduced the shock, it was necessary to provide shock absorbers in order to eliminate the resulting oscillation which otherwise more than offset the reduction in the intensity of the initial shock.

Where the ground wire has the properties of the shock absorber, it will not only reduce the crest voltage or bump, but will dissipate the energy stored in the power conductor.

Where the resistance of the ground wire is low, the current induced in the ground wire by a traveling wave or oscillation will create but small loss so that a low-resistance ground wire will not have the dissipating or shock-absorbing properties of a high-resistance ground wire. If we are to obtain the benefit of a low-resistance ground wire both from the standpoint of reducing the crest voltage and through the absorption of energy in the traveling wave, it is necessary to adopt a new scheme of installation. In this scheme it is proposed to sectionalize and insulate the ground wire, forcing the induced currents over discharge gaps which will dissipate energy. In order that the ground wire may hold down the crest voltage in the vicinity of the disturbance, a shunt gap is provided at the insulated supports. This shunt gap discharges and reduces the potential from ground wire to earth. An installation of this kind not only keeps down the maximum voltage in the vicinity of the disturbance, but can be made to absorb the traveling wave or oscillation. The absorption of energy tends to cut down the time-voltage effect, tending to flash the insulator and thereby reduces the tendency to flash at a distance. The absorption of energy will also be beneficial in keeping down the magnitude of the surge entering the station. From the electrical standpoint, resistance in the ground wire may be of material advantage and where low-resistance ground wires are used, it would seem that provision should be made so that they will dissipate the energy of the traveling waves or oscillations.

Where ground wires are located near stations, attention should be given to developing the electrostatic capacity between ground wire and conductors as far as possible. This increased electrostatic capacity together with the electrostatic capacity of the bus structure and connected equipment will do much to keep down the maximum voltage in the station. It would seem that the increased electrostatic capacity of the station is a much greater factor in keeping down the maximum voltage than the impedance of a choke coil. In extra high-voltage transformers, more dependence is placed in the circuit upon absorbing resistances than upon reactance coils. As a matter of fact, where break-downs are quite frequent with reactance coils, these break-downs have disappeared where absorbing resistances are used. Where an absorbing resistance cannot be placed between the line and a large station, an absorbing resistance can be placed in a ground wire. As the energy must come from the power conductor, the same general result will be accomplished as in the case where the absorbing resistance is used directly in the circuit.

**W. W. Parker:** (communicated after adjournment) I feel in very strong agreement with J. F. Peters' suggestion that the potentiometer used in connection with the klydonograph requires some special investigation and further research. We got some rather startling results from a klydonograph installation on our 132-kv. system last January, which led to some investigations. It was found that positive figures can be produced by sprinkling water over the potentiometer, and by momentarily bridging out one of the insulators forming part of the potentiometer string. Each figure obtained by sprinkling the potentiometer is positive. The rays radiate out from the center with no evidence of any negative figures. Some of these figures are as high as fifteen times normal.

The potentiometer consists of five Faradon condenser-type insulators in series, the klydonograph being connected across the last insulator. The last insulator is approximately ten times the capacity of the others.

**C. F. Harding:** (communicated after adjournment) The data recorded and summarized in the paper by Messrs. Hemstreet and Eaton provide one more distinct advance in the investigation of high-voltage surges and the analysis of their causes. The surge recorders have apparently provided more information regarding the number, magnitude, and locality of such surges upon transmission lines than any instruments have furnished which have been available previous to this time.

However, such an instrument is admittedly very approximate in its quantitative measurement, particularly with respect to the steepness of the wave front and duration of the tail of the surge, and is likely to be qualitatively misleading with respect to initial polarity and indication of the oscillatory nature of the discharge. The large number of surges which were recorded with almost equal magnitude at all stations, apparently having medium damped characteristics and yet rising to 7.7 times normal line voltage and coinciding with switch trip-outs, is, of course, such as to cause the more serious and widespread interruption to service. These should therefore be studied most thoroughly in future investigations. Fortunately, such surges may now be recorded and analyzed by means of the cathode-ray oscillograph and the polarity, magnitude, and duration of the medium and slightly damped tails of the surge may be more accurately determined and studied.

The contribution of this paper to the much discussed subject of the protective value of the ground wire, furnishing for the first time concrete test data of parallel exposures under similar conditions both with and without the ground wire, has been greatly needed to bring to a definite conclusion the arguments of past years which have been based upon exposures of different types in various localities and the resulting opinions of engineers necessarily dependent upon rather meager test data. These test data are significant not only because of their proof of the protective feature of the ground wire, but particularly because of the reduction in the number of surges which ranged from four to eight times normal line voltage and the apparent elimination of those between eight and eleven times normal which appeared upon the parallel line. Furthermore, the importance of thorough grounding of the ground wire at each tower has been demonstrated by the test voltages accumulated at the center of the span.

Although the conclusion is recorded with reference to Figs. 11 and 12 that "no definite relation exists between the magnitude of surge voltages measured and conductor height," it would appear from inspection of these graphs that the upper wire on both lines is withstanding more and higher voltage surges than the lower wires, particularly for surges up to five or six times normal. It would be of interest to know if the original data, or those not included in these charts, tend to neutralize the value of such a conclusion.

**J. E. Clem:** (communicated after adjournment) Mr. Lewis in his paper gives the maximum voltage found as resulting from switching, but gives no data in regard to the length of the wave front. The wave front should be known so that new lines may be designed with enough insulation to withstand these surges. This discussion will present some data which should help in deciding whether 60 cycle or impulse strength applied when considering the voltages produced by switching surges.

In Table V, Lewis gives the maximum voltages found due to switching and in the text states that load switching is not severe and that switching off is more severe than switching on. Although not mentioned specifically the voltages due to opening a short circuit are included in the tabulation. It is also stated that these surges are usually highly damped and therefore of short duration. It is seen from this table that the highest voltage is about 5 times the normal crest voltage line to neutral. Since this ratio is not exceeded over the operating range from 110 kv. to 220 kv. it can be used safely for design.

TABLE A

WAVE FRONT OF SWITCHING SURGES

NEW ENGLAND POWER CO.

Normal Voltage Line to Neutral = 90 Kv.

| Between 100 Kv. and 200 Kv. | | Between 200 Kv. and 300 Kv. | | Between 300 Kv. and— | |
|---|---|---|---|---|---|
| Kv. | Front Mc. S | Kv. | Front Mc. S | Kv. | Front Mc. S |
| 120 | $10^5 - 10^6$ | 210 | $10^4 - 10^5$ | | |
| 120 | $10^5 - 10^6$ | 240 | $10^5 - 10^6$ | | |
| 120 | $10^5 - 10^6$ | 240 | $10^5 - 10^6$ | | |
| 120 | $10^5 - 10^7$ | 240 | $10^5 - 10^6$ | | |
| 120 | $10^5 - 10^6$ | 220 | $10^3 - 10^5$ | | |
| 120 | $10^5 -$ | 220 | $10^3 - 10^5$ | | |
| 120 | $10^5 - 10^7$ | 200 | $10^4 - 10^5$ | | |
| 140 | $10^5 -$ | 240 | $10^4 - 10^5$ | | |
| 110 | $10^4 - 10^5$ | 240 | $10^4 - 10^5$ | | |
| 160 | $10^4 - 10^5$ | | | | |
| 150 | $10^4 - 10^5$ | 270 | $10^2 - 10^5$ | 360 | $10^2 - 10^5$ |
| 150 | $10^4 - 10^5$ | 280 | $10^3 - 10^5$ | | |
| 150 | $10^5 - 10^6$ | 260 | $10^3 - 10^5$ | | |
| 150 | $10^5 -$ | 260 | $10^3 - 10^5$ | | |
| 150 | $10^4 - 10^5$ | 270 | $10^3 - 10^5$ | | |
| 160 | $10^4 - 10^5$ | | | | |
| 180 | $10^4 - 10^5$ | | | | |
| 180 | $10^4 - 10^5$ | | | | |
| 180 | $10^5 - 10^7$ | | | | |

TABLE B

WAVE FRONT OF SWITCHING SURGES

PENNSYLVANIA POWER & LIGHT CO.

Normal Voltage Line to Neutral = 180 Kv.

| Between 300 Kv. and 400 Kv. | | Between 400 Kv. and 500 Kv. | | Between 500 Kv. and 600 Kv. | | Between 600 Kv. and— | |
|---|---|---|---|---|---|---|---|
| Kv. | Front Mc. S | Kv. | Front Mc. S | Kv. | Front Mc. S | Kv. | Front Mc. S |
| 340 | $10^4 - 10^5$ | 410 | $10^4 - 10^5$ | 540 | $10^3 - 10^5$ | 630 | $10^3 - 10^5$ |
| 320 | ? | 410 | $10^4 - 10^5$ | 540 | $10^3 - 10^5$ | 600 | $10^3 - 10^5$ |
| | | 410 | $10^4 - 10^5$ | | | | |
| | | 410 | $10^4 - 10^5$ | | | | |
| | | 410 | $10^4 - 10^5$ | | | | |
| 360 | $10^4 - 10^5$ | 480 | $10^4 - 10^5$ | 575 | $10^3 - 10^5$ | 720 | $10^3 - 10^6$ |
| 340 | $10^4 - 10^5$ | 450 | $10^3 - 10^5$ | 560 | $10^4 - 10^5$ | | |
| 340 | $10^4 - 10^5$ | 480 | $10^4 - 10^5$ | | | | |
| 360 | $10^4 - 10^5$ | | | | | | |
| 360 | $10^4 - 10^5$ | | | | | | |

TABLE C

WAVE FRONT OF SWITCHING SURGES

OHIO POWER CO.

Normal Voltage Line to Neutral = 108 Kv. Crest

| Between 200 Kv. and 300 Kv. | | Between 300 Kv. and 400 Kv. | | Between 400 Kv. and 500 Kv. | | Between 500 Kv. and | |
|---|---|---|---|---|---|---|---|
| Kv. | Front Mc. S | Kv. | Front Mc. S | Kv. | Front Mc. S | Kv. | Front Mc. S |
| 200 | ? | −300 | F? | −410 | F10 | +550 | $10 - 10^4$ |
| 240 | $10^5$ | +300 | $10^4$ | +420 | $10^2 - 10^3$ | +550 | $10 - 10^4$ |
| −240 | $10^5$ | +320 | $10^4 - 10^5$ | 440 | $10^3 - 10^5$ | +520 | $10 - 10^2$ |
| −240 | $10^5 - 10^6$ | +320 | $10^4 - 10^5$ | −440 | $10^2 - 10^5$ | | |
| +220 | $10^4 - 10^5$ | −330 | $10^5 - 10^6$ | +430 | $10^3 - 10^5$ | | |
| +200 | $10^5 - 10^6$ | +300 | $10^5 - 10^6$ | +400 | $10^2 - 10^5$ | | |
| +200 | $10^5$ | +320 | $10^5 - 10^6$ | +430 | $10^2 - 10^5$ | | |
| −250 | $10^4 - 10^5$ | +345 | $10^3 - 10^5$ | +410 | $10 - 10^3$ | | |
| −210 | $10^4 - 10^5$ | −300 | $10^3$ | | | | |
| 230 | $10^5$ | 310 | $10^3 - 10^5$ | | | | |
| −250 | $10^4 - 10^5$ | −330 | $10^4 - 10^5$ | | | | |
| −230 | $10^3 - 10^4$ | −330 | $10^3$ | | | | |
| −290 | $10^4 - 10^5$ | −360 | $10^3 - 10^4$ | +450 | $10 - 100$ | | |
| −295 | F$10^3$ | +370 | $10^3 - 10^5$ | −480 | $10^2 - 10^4$ | | |
| 270 | F100 ? | −395 | F100 | +480 | $10 - 10^3$ | | |
| +280 | $10^4 - 10^5$ | −350 | $10^3 - 10^5$ | | | | |
| −280 | $10^4 - 10^5$ | +395 | $10^3 - 10^4$ | | | | |
| −270 | $10^4 - 10^5$ | +380 | F100 | | | | |
| +290 | $10^4$ | 370 | $10^3$ | | | | |
| −295 | $10^4 - 10^5$ | −380 | $10^3 - 10^5$ | | | | |
| −275 | F$10^4$ | −370 | $10^3 - 10^5$ | | | | |
| −293 | $10^3 - 10^5$ | 350 | $10^3 - 10^5$ | | | | |
| −270 | $10^4 - 10^5$ | +360 | $10^3 - 10^4$ | | | | |
| 280 | $10^4$ | 360 | $10^2$ | | | | |
| −260 | $10^4 - 10^5$ | +370 | F$10^3$ | | | | |

The accompaning three tabulations give an analysis of switching surges found on three of the systems mentioned in Table V. The data have been tabulated to show the magnitude of the crest voltage and the time to reach the crest; that is, the wave front. The wave front was obtained by the method outlined in Lewis's paper. A study of these data indicates that at the lower voltages the wave fronts are relatively long, while at the higher voltages there might be said to be a tendency toward shorter wave fronts. Although all the surges, except one, above four times normal could have had a wave front as fast as 100 microseconds, it doubtless would be better to consider them all slow and use the 60-cycle flashover strength of the insulators in figuring the number of units required to prevent flashover from switching surges.

These switching surges may happen when the line insulators are wet and this should be considered. For a standard precipitation of 0.2 in. rain per minute the 60-cycle flashover is approximately 80 per cent of the dry flashover. This precipitation is not rain but is really a deluge. At half the standard precipitation the flashover is about 7 per cent higher, according to Peek, and for the ordinary heavy rainstorms is no doubt somewhat higher.

The lightning flashover of a string of insulators is the same wet as dry which indicates that the effect of moisture decreases as the wave front grows shorter. In view of the fact that the surges having a magnitude of five times normal probably have a wave front faster than the 60-cycle wave front, it is quite possible that the effect of rain is somewhat less than at 60 cycles. Also Wade and Smith in an article entitled "Time Lag of Insulators," *Elec. World*, Aug. 18, 1928, give data which indicate that the flashover voltage of suspension insulators obtained with a wave front corresponding to 60 cycles may be somewhat higher than that obtained by the usual method of determining the 60-cycle flashover voltage. These two facts indicate that the ratio of wet to dry flashover for these switching surges will be higher than for 60 cycles. From the foregoing it appears that the dry 60-cycle flashover voltage of the insulators can be used in estimating insulation required for switching surges.

Studies of existing systems have shown that the average line insulation will stand about six times normal voltage. This is enough to withstand any low-frequency disturbances to which the lines may be subjected, whether due to dropping of load, switching, or arcing grounds. It appears that a line insulated for five times normal lag voltage will not flash over during switching transients, but since existing lines have an average of six times, it would be better to use six times normal leg voltage as the required insulation strength at 60 cycles.

**R. H. George:** (communicated after adjournment) The percentage of apparently oscillatory discharges recorded by Messrs. Hemstreet and Eaton seems quite high, but as pointed out, this may be due largely to the limitations of the surge recorder rather than to actual oscillatory surges. Some of these records may result from a series of successive discharges from cloud to earth similar to those illustrated in Dr. Humphreys' book "Physics of the Air," pages 368-372. Dr. Humphreys shows one photograph taken by Larsen with a revolving-mirror camera in which six successive discharges take place along the same path at intervals of from 4 to 10 milliseconds. If such a series of discharges took place in the vicinity of a transmission line, the rapid fluctuations in the field might give rise to records of reversed polarity although the actual discharges were in one direction.

It is quite probable that the question of oscillatory surges on transmission lines can only be solved by the use of the cathode-ray oscillograph, on the use of the oscillograph and surge recorder together.

**W. W. Lewis:** Mr. Perry asked about the effect of choke coils on the voltage reaching the arresters. That is what we are trying to find out in our investigation. All the data we have on the subject at present are given in Mr. Sporn's and my papers. The data are rather confusing and do not indicate definitely whether choke coils are beneficial or not. We are, however, going to use them until we know more about the subject.

Mr. Perry also asked to what percentage of normal voltage a modern arrester will limit a surge. This has been very well answered by Mr. K. B. McEachron in a paper entitled "Protection of Station Equipment on High-Voltage Transmission Lines" which appeared in the *General Electric Review* of May 1928. In this paper it is shown that oxide-film arresters limit the voltage of a surge to certain values which depend on the wave front of the surge. These values vary from about 1 kv. per cell to about 1.8 kv. per cell. The last-named value is the voltage corresponding to the steepest wave fronts, *i. e.*, of the order of one-fourth microsecond. Such a front is steeper than any that we have been able to measure on transmission lines and corresponds with the wave in Mr. Peek's laboratory which we have used as a reference in giving the flashover value of insulator strings.

From this statement it will be apparent that the fewer the cells used, the better the protection obtained. A certain minimum number of cells is required, however, to prevent the arrester from failing under 60-cycle voltage when the voltage runs away due to the dropping of load. If this runaway voltage can be maintained at a low value, then the number of cells may be decreased and the protection will be improved.

Mr. Perry also asked that Table IV be supplemented by the average height of conductor for Line H-8. This average height, I believe, is about 45 ft.

In Mr. Foote's discussion he refers to the 60-cycle flashover value of line insulation as about three times normal. On the average system the 60-cycle flashover is usually about six times normal, *i. e.*, six times the crest value of the line-to-neutral voltage. For example: On Mr. Foote's own 140-kv. system, normal voltage is about 114-kv. crest value line-to-neutral. The 60-cycle flashover of ten standard disks is about 765-kv. crest value, or about 6.7 times normal. The impulse flashover with steep wave is in the neighborhood of 1400 kv. or about 12 times normal. An examination will disclose that the majority of transmission lines are insulated for at least six times normal, 60 cycle voltage, and from 10 to 14 times normal against impulse flashover.

The flashover voltage of a string of insulators varies from the 60-cycle value to a very high value under impulse. Any number of impulse values may be obtained, depending on the steepness of the wave front and the duration of the wave. The figure of 10 to 14 times normal mentioned as impulse flashover is based on a particular wave of steep front and long tail. If we had a steeper wave we might even get a higher value. As shown in Table IV of my paper, the highest voltages recorded in the 1927 investigation vary from 7 to 12 times normal, which check fairly well with the estimated impulse flashover.

In regard to Mr. Michener's discussion: the resistance of the tower footing has a great deal of effect on the operation of the ground wire. If the tower footing has a high resistance the ground wire is, in effect, an insulated wire, and will do very little good in reducing surge voltage.

In the particular territory discussed by Mr. Michener, it might be that the soil is composed largely of sand and rocks. This condition will give a very high tower-footing resistance which not only nullifies the grounding of the ground wire but apparently has the effect of increasing the height of the tower. In other words, a high ground resistance indicates that the water level is considerably below the earth surface and the tower in effect is much higher than indicated by the height above the earth's surface itself. This allows lightning to build up a higher voltage on the conductors than would be expected. Mr. J. G. Hemstreet brought out this effect very well in a paper entitled *Recent Investigation of Transmission Line Operation*, which appeared in A. I. E. E., TRANS., Vol. 46, 1927, page 835.

**J. R. Eaton:** There is one point in connection with safety that has been emphasized in the report on the Pennsylvania Power and Light Company presented by Mr. Smeloff.

The line was grounded at numerous places during the installation of a ground wire. Even with this line grounded at various places, there were very high voltages recorded—I think over a million volts. On the Consumers' line we recorded over 35,000 volts at mid-span of a ground wire, where, of course, it was grounded at both ends of the span.

That certainly emphasizes the necessity of grounding a line at the point where men are working on it, especially under lightning conditions. A ground that is located even a few spans away certainly does not offer adequate protection to men who are working on the line.

Someone asked for an explanation of the fact that surges recorded at mid-span of the ground wire had low values compared with that recorded simultaneously on the line wire. On the ground wire the maximum voltage recorded was 35 kv. at mid-span while at the tower it was several hundred kv. It is possible that the surge originated at some point down the line, and the transient traveled along the conductor without being reduced in value to any great extent, whereas on the ground wire, the section on which the surge recorder was connected was in a weak part of the field and received only a small part of the voltage.

In some recent inspections we have found two distinct kinds of burns on our insulators. There is one type which we feel sure is caused by a power arc. This resembles that produced by laying a cigarette on a varnished surface. That undoubtedly comes from the power arc.

There is another type of burn on the procelain which might be described as appearing as though some thin molasses had been spilled near the cap of the insulator and then run in a narrow stream to the end of the insulator. This type of burn has been observed on insulators which have been flashed over by impulses from lightning generators as well as on insulators in the field. We feel reasonably sure these burns are caused by the lightning discharge itself. Burns of this type are frequently found where the power arc type of burn is also found, indicating that possibly there had been a lightning flashover followed by the power arc.

In some cases, however, every unit in a string will have the lightning burn on the porcelain, showing almost a complete cascade of the lightning discharge, but there will be no power-arc burns at all. That may be an explanation of the fact that in some cases we have recorded very high voltages on lines without having them trip out. Apparently the power arc did not follow the lightning flashover.

**J. G. Hemstreet:** The investigations that are being made on the various transmission systems and in the laboratories are gradually determining exact conditions which create perhaps the greatest hazard to power transmission.

The klydonograph has been of great value in determining the magnitude of the surges set up and has quite definitely shown that surges due to causes other than lightning are not so serious as was thought a few years ago. The results of the klydonograph investigations as shown by these papers have been a little disappointing due to the uncertainty of the meaning of some of the figures recorded. However, this difficulty has been done away with and with the proper type of potentiometer, a better set of records should be obtained by these instruments.

We believe that some of the most valuable information has been obtained by careful inspections of transmission lines and by keeping records of the number of insulator flashovers found by these inspections. The insulator string and its performance under the abnormal conditions in the lines is, in the last word, the real indicator of the severity of the surges that are taking place and it would be well if more of the operating companies would make these careful investigations so that a greater quantity of data will be available for study.

The cathode-ray oscillograph seems to offer a means of securing information as to the steepness of the wave front and other characteristics of the surges that are under investigation. It is our understanding that an oscillograph of this type, together with other instruments, is to be used by the Westinghouse Electric and Manufacturing Company in securing data on one of the high-voltage lines in Tennessee and that the General Electric Company are making a somewhat similar setup on a line in Pennsylvania. The Consumers Power Company in continuing its investigation of lightning disturbances, has obtained the use of a type of cathode-ray oscillograph which has been developed in the High Voltage Laboratory of Purdue University. This instrument will be connected to the lines of this company and it is hoped that more exact information as to the character of the surges on the system will be secured. This, together with the investigation on other systems along the same line, will perhaps give us information that will be of great value in connection with the design of transmission lines and substations.

**Philip Sporn:** Mr. Michener's point with regard to the effectiveness of the ground wire, I think, is very well taken. The papers, as a whole, do not bring out the effectiveness of the ground wire as clearly as do other operating data and I should like to refer Mr. Michener to the series of papers that has been presented during the last three years before the Institute, on the lightning experience that we had with the Philo-Canton line both before and after ground wires were installed, which throw some light on the ground wire's effectiveness.

Mr. Foote brought up a point with regard to choke coils. When we first started our klydonograph layout to study the effectiveness of the choke coils we had pretty high hopes. We thought we would get come definite information either pro or con. The first thing that we ran into was a few surges that came in where we found on one side of the choke coil some 200 kv. positive and on the other side we found the same negative, a reversal of polarity taking place through the choke coil. On going to the next tower out from the station we found that it was still positive. We did not believe this. There are so many surges that can be superimposed one on top of the other, or combined due to reflection, and since the klydonograph records only the one maximum voltage which exists, the limited information that we have obtained so far cannot possibly be conclusive. However, we do believe that this much has been shown. In so far as it can be said that the choke coil is either a benefit or a hindrance in connection with a lightning arrester the data showed definitely that it is certainly no worse than neutral and very often beneficial. Theory, of course, checks that up also.

Mr. Austin made the statement that attenuation is much less rapid with the ground wire than without it. This is obviously not so. He is right if he means that due to the fact that where a ground wire exists the possible amplitude of the wave is initially cut down and therefore the rate of attenuation on this reduced wave is much smaller than it would have been on the wave without a ground wire. Otherwise he is not right, since the ground wire helps reduce the amplitude of the wave by acting as an absorbing medium.

**N. N. Smeloff:** The type of potentiometer used on our system produces slightly damped figures. We have not discarded these figures from our study, but classified them and used them. These uses were made with a reservation, *i. e.*, it is without doubt now established that the slightly damped figures are produced by 60-cycle potential and this type of potentiometer; however, the highly damped figures may be present, but obscured by the slightly damped figures. This has been proved by the fact that during some trip-outs and flashovers of the line, only the slightly damped figures were obtained on the recorder films.

The study during 1928 is more extensive: more instruments and additional 220-kv. line are used. The potentiometers for the surge-voltage recorders have been modified in such a manner that no slightly damped surges are produced that would obscure the recorder films.

It would be rather premature to draw conclusions about the operation of our new 220-kv. line. It went through just about two months of lightning season operation without trip-outs. Surge-voltage recorders are installed and we expect to obtain valuable data. On the old line, Wallenpaupack-Siegfried, we again had several flashovers. The flashovers occurred on the unprotected section of the line as well as on the section where the overhead ground wire was installed. So again we are not in a position at this time, to make any definite conclusions on the value of overhead ground-wire protection.

# Research

## ANNUAL REPORT OF THE COMMITTEE ON RESEARCH*

*To the Board of Directors:*

### 1. The Research Committee

In order to increase the activities and usefulness of the committee it seemed desirable to appoint working subcommittees to take charge of the several important divisions of the work. The following have been appointed:

Subcommittee on Placing of Research Subjects with Suitable Persons and Organizations—(D. W. Roper, Chairman).

Subcommittee on Training of Research Men—(V. Bush, Chairman).

The membership of the committee should be so chosen that a considerable percentage of the membership of the subcommittees will overlap from year to year. The appointment of several other working subcommittees is under consideration. It is hoped that the working committees of the Research Committee will eventually make it as effective in the research field as similar working committees have made the Standards Committee in the standardization field. It is suggested that consideration be give to changing the Research Committee from a technical committee to a standing committee.

### 2. Examples of Outstanding Research During the Year

The spectacular contribution to the communication art in the past year has been television. This has a particular interest from the standpoint of research since it was made possible by improvements in mechanical and electrical facilities that have sprung directly from research work, instances of which are improvements in photoelectric cells, in methods of amplification, in gaseous discharge lamps for producing visible effects from rapidly changing electrical signals, and improved methods of synchronization of widely separated points.

Other developments are the Knowles tube and its application to the televox, starting electrical equipment at a distance, and the development of a 50 million-cycle tube with a 10-kw. output. The increase in power of many American and foreign radio stations, making them international in their effects, raised the question as to whether or not the national standards of radio frequency of various governments were in agreement. During the past year a check was made by Dr. Dellinger of the Bureau of Standards in the National Laboratories of England, France, Italy, and Germany by means of the temperature controlled piezo-oscillator. The average difference was only 0.03 kilocycles in 1000. This is much smaller than the variation of 0.5 kilocycles allowed broadcasting stations in this country.

A radio beacon system establishing an invisible but infallible course along which aviators can fly regardless of weather conditions, has been sufficiently perfected by the Bureau of Standards so that routine use of it on regular airways is beginning.

A most impressive and historic event took place at the Winter Convention this year. Through the courtesy of the American Telephone and Telegraph Company and the British Post Office a joint meeting took place over the radio telephone between the Institution of Electrical Engineers of Great Britain meeting in London and the American Institute of Electrical Engineers meeting in New York.

There has been a number of researches during the past year of a fundamental nature. Particular mention might be made of the work of Davison and Germer regarding the diffraction of electrons by crystals of nickel. They prove that electrons behave at reflection as though they had wavelengths dependent upon their velocity. The discovery and measurement by J. B. Johnson of an electromotive force due to the thermal agitation within conducting materials is also of importance.

Among new tools which increase the scope of fundamental work in physics and engineering might be mentioned the operation by Coolidge of three cathode ray tubes in series at 900,000 volts.

A lightning generator producing impulses of over 3,500,000 volts also offers an important tool for the extension of fundamental work in physics and engineering.

Considerable important work on insulation measurements and lightning measurements on transmission lines is being carried out.

An analysis of the important fundamental research of the country shows that a fairly large percentage is still being done by the large industrial laboratories such as those of the American Telephone and Telegraph, the Westinghouse, and the General Electric Companies.

### 3. Research Organizations

While the large manufacturing companies are still doing a considerable percentage of the important fundamental research, there are indications that our colleges and other organizations will play an increasingly important part, as they should. It is reassuring that funds are more readily available than ever before.

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*COMMITTEE ON RESEARCH:

F. W. Peek, Jr., Chairman.
H. D. Arnold,
Edward Bennett,
V. Bush,
E. H. Colpitts,
W. F. Davidson,
W. A. Del Mar
W. P. Dobson,
V. Karapetoff,
A. E. Kennelly,
S. M. Kintner,
M. G. Lloyd,
C. E. Magnusson,
E. W. Rice, Jr.,
D. W. Roper,
C. H. Sharp,
C. E. Skinner,
R. W. Sorensen,
J. B. Whitehead.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

An important new factor in research has been given us in the Bartol Foundation, the result of a large bequest. Dr. Swann, director of this organization, which will undoubtedly have a very important influence on future American research, has kindly supplied the following information regarding it.

"The Bartol Research Foundation of the Franklin Institute is at present located in three houses at 127 No. 19 St., Philadelphia. These houses were made over a few years ago for laboratory purposes, and comprise ten research rooms, a library, glass blowing room, shop, and accommodations for storage battery equipment, etc.

"The present site is only temporary, pending the completion of a new laboratory. By an arrangement with Swarthmore College, it has been decided to build upon the campus of the college. By this arrangement the laboratory secures a site free from the disturbances of traffic and protected as regards its surroundings. It secures a congenial academic atmosphere such as most of its members have been accustomed to. On the other hand, while there is no affiliation to the college itself, the college feels that our presence will rebound to its advantage in many ways, and we hope and feel that this will be so.

"The laboratory will be about 110 ft. long and 50 ft. wide, comprising a basement, first and second floor, and a subbasement large enough to accommodate one spectroscopic room. The attic will also accommodate two rooms. The basement floor includes a large machine shop, wood shop, a glass blowing shop, and a battery installation, together with a room for miscellaneous technical operations.

"The first floor will be devoted to research laboratories and a workshop for the fellows, and the director's laboratory and offices. On the second floor there will be an apparatus room, a lecture room and large library, an optical shop, small office and research rooms, and the attic will provide for a chemical laboratory. The whole is designed to accommodate about ten or fifteen fellows together with the director, and research assistants. At the present time the technical staff comprises one instrument maker, one mechanic and an apprentice, also a full time glass blower and a general utility man.

"The main activities of the laboratory will be directed to the investigation of scientific problems pertaining to the fundamentals of electrical science. This is, of course, rather a wide field and comprises practically the whole field of modern atomic structure under its head.

"While the laboratory is primarily for research, it is proposed to provide in it such conditions for continued mental development as are desirable for young men of the post Ph. D. type. The director and the individual fellows take turns in lecturing to the group upon various phases of modern physics, particularly in relation to atomic structure. The Bartol Foundation has been fortunate in having many lecturers from American institutions, and a fund has been appropriated for the purpose of bringing from time to time distinguished physicists to stay here for a period of two or three months and give the laboratory the benefit of their intellectual contact.

"At the present time, the laboratory is accommodating six fellows on its payroll, one National Research Council fellow, a guest fellow, and one research assistant. It is possible that two or more National Research Council fellows will be here next year. Since October 1, 1927, eight publications of the Bartol Foundation have appeared in the *Journal of the Franklin Institute* and six publications of the results of investigations at the laboratory have been presented before the American Physical Society.

The following investigations are at present under way at the laboratory.

1. An investigation on the reflection of atoms of atomic hydrogen from crystal surfaces.
2. The production of, and characteristic properties of X-rays produced by protons.
3. An attempt to detect a magnetic field resulting from the rapid rotation of a copper sphere.
4. An investigation concerning the pulling of electrons out of metal under intense electric fields.
5. An investigation of the loss of velocity of electrons as a result of the production of characteristic X-rays in the passage of the electrons through thin metallic films.
6. A series of investigations pertaining to the mechanisms involved in the production of the electric arc between carbon electrodes and metal electrodes.
7. The design of an apparatus for the production of high electrical potentials.
8. A series of investigations having to do with the effect of high-frequency fields on optical and allied properties of transparent media.
9. An investigation of the nature of excitation of various lines in the mercury arc.
10. An investigation of the part played by cosmic radiation in the production of radio activity.
11. An investigation on the electrical conductivity of non-aqueous solutions of solvents.
12. A theoretical investigation on the scattering of X-rays by matter.
13. The preparation of a paper involving the results of observations of the cosmic radiation, made at Pike's Peak and New Haven."

* * * * *

The Public Utilities are entering the research field and are not only supplying money to colleges, but are also operating research laboratories. As an example, the Utilities Research Commission, made up of representatives of the utilities of which Mr. Samuel Insull is the head, has arranged for investigation of cable insulation at the University of Illinois, of lightning protection at Purdue, and of properties of insulation at the University of Chicago, etc.

Important work is being carried on in insulation by committees of the National Research Council, the N. E. L. A., etc.

The Research Committee of the Institute serves as the Advisory Committee on Electrical Engineering to the National Research Council and is also closely cooperating with the Engineering Foundation.

### 4. The Training of Research Workers

Results in research depend more upon men than money and laboratories. It is still a fact that in spite of organized research and group working in large laboratories, outstanding results are generally due to the genius or inspiration of the right man. While such men cannot be manufactured in our colleges, natural ability can be developed under the proper influence. Apparently the colleges are making progress, as indicated by the report of Professor V. Bush, Chairman of the Subcommittee on Training of Research Engineers, which follows:

"There is a considerable increase in the emphasis being placed on graduate study and hence on engineering research, which is an important part of such study, in schools of advanced standing among the technical educational institutions of the country. The total graduate enrolment in engineering colleges on the basis of the statistics of the United States Bureau of Education was 1114 in 1925-26, 1566 in 1926-27, and 1669 in 1927-28. The principal branches are civil, mechanical, electrical, and chemical engineering and in 1925-26 these four included 807 out of the 1114. During the three years cited the figures for civil engineering are 156, 240, and 266; those for mechanical engineering 256, 206, and 240; and those for electrical engineering, 281, 434, and 468. Of course these figures include many graduate students in technical schools where there is little important research being carried on; and perhaps only 30 or 40 per cent are in contact with research of a high order in their institutions. Still it is evident that there is an increasing tendency toward work of this nature in technical schools, and that this tendency is particularly marked in recent years among students of electrical engineering.

"It is believed that this tendency toward graduate study and research is a healthy development, and that its growth should be encouraged by industry and by the profession. Perhaps the greatest encouragement that can be given is for the students to learn that real achievement in advanced work is highly regarded by the profession wherever such is the case. There is no doubt that the recent analysis by the Bell System of the correlation between high grades in college and success in later work on their staff, as presented by President W. S. Gifford in Harper's Magazine for May 1928, will have a real vital influence in encouraging a scholarly attitude on the part of undergraduates generally. Similarly, if the industry and profession find by experience that graduate study of a serious sort is worth while for students of outstanding ability, the knowledge that such a conviction exists will be of the greatest value in raising the tone of graduate study and research in the engineering colleges. It is to be hoped, therefore, that the membership of the Institute will watch this development of graduate study and research with interest, and that, if they believe it is a desirable thing for the progress of electrical engineering, they will make known their convictions in an effective manner.

"Direct aid of such work by industries is, of course, valuable, particularly when the research carried on at educational institutions is carefully correlated with the regular instruction so that the full pedogogical benefit of working in a research atmosphere is obtained. Some years ago, for example, when graduate study in engineering schools was just beginning to grow, the American Telephone and Telegraph Company contributed directly to electrical engineering research at the Massachusetts Institute of Technology, and the work resulting was conducted in close liaison with the instructional program of that institution. The research results obtained were themselves worth while, but more important was, undoubtedly, the influence upon the student body and the early exposure of students to the research point of view.

"It is becoming increasingly evident in recent years that electrical engineering is adopting and applying more and more of mathematical and applied physics and chemistry. Hand in hand with this adoption must go the training of research workers of high calibre who have the engineering attitude, if the greatest progress is to be made. Industrial research is being well carried on by the industry, but the principal supply of research workers must come from the colleges; and, as electrical engineering becomes more and more complex, the training in advanced study and research in the technical schools must continue to expand as it has done in recent years to meet the need."

F. W. Peek, *Chairman.*

# Electrophysics

## ANNUAL REPORT OF THE ELECTROPHYSICS COMMITTEE[*]

*To the Board of Directors:*

The personnel of the Committee and its general policies have been practically the same as during the preceding Institute year, so that this report is essentially a continuation of the last year's report. A steady endeavor has been made during the year to connect some practical engineering problems with the achievements and efforts of modern physics, both experimental and mathematical. In these endeavors we have been materially assisted by the two liaison representatives of the American Physical Society, authorized by the Board of Directors in 1927. As a further step in the same direction, the committee arranged for a general lecture on *The Nature of the Electric Arc* which was ably delivered by Professor K. T. Compton at the 1927 Summer Convention in Detroit.

The success of this lecture led to an authorization of another lecture at the 1928 Winter Convention. The subject of this lecture was *The Earth's Electric Charge*, and it was delivered by Dr. W. F. G. Swann of the Bartol Research Foundation. This lecture was also quite successful, and as a result a lecture on geophysics, by Dr. C. A. Heiland, was presented at the Denver convention. The committee recommends that a lecture on some topic in "border sciences," such as physics, chemistry, mechanics, and mathematics, be scheduled at all our large conventions, as a stimulus to young engineers in fostering the progress of the art and as a preventative against in-breeding. In particular, for the next Winter Convention, the committee suggests a topic on spectrum analysis in application to the constitution of the stars. During such a lecture, much of the latest progress in the atomic structure could be explained on a specific problem.

### PAPERS PRESENTED

Quite a number of papers related to electrophysics have been presented at or scheduled for various Institute meetings during the period covered by this report. The titles and authors of several of these papers are mentioned below in connection with the individual topics. The papers themselves will be found in the JOURNAL and the TRANSACTIONS for 1927 and 1928.

### ELECTRICAL DISCHARGES IN GASES

*Disruptive Discharges.* A simple relation for determining the voltage across a spark-gap during the course of breakdown has been given, but the constant entering into this relation has been found to vary widely under different conditions of test. (Toepler, Mueller, *Arch. f. Elektrotech.*). Cathode ray oscillographic study of spark-gaps also gives results incompatible with the Toepler spark constant (Tamm, *Arch. f. Elektrotech.*). Photographs of incompleted sparks indicate the need for modification of the Townsend sparkover theory for high voltages at atmospheric pressures. (Torok, A. I. E. E. QUARTERLY, April 1928). The distortion of the electric field by a space charge in the early stages of the formation of the spark may be important (Loeb, *Journ. of Franklin Inst.*). Whether negative ions are generated near the cathode by collisions of positive ions with gas molecules, or by radiation acting photoelectrically upon the cathode, has been actively debated. (Taylor, Townsend, *Phil. Mag.*). Experiments on "three-point spark-gaps" favor the photoelectric action. (Morgan, Thomson, *Phil. Mag.*). Lowering of the sparking potential under sustained high-frequency applied voltage has been observed. (Reukema, A. I. E. E., TRANS., 1927).

*Corona.* Further studies on the mechanism of corona, bringing out the part played by space charges, have been made (Carroll & Lusignan, QUARTERLY TRANS. 1928, Peek, A. I. E. E.TRANS., 1927). A quantitative theory giving excellent checks with observations has been developed for the d-c. corona. (Holm *Arch. f. Elektrotech.*)

*Arcs.* There has been great interest in the theory of the electric arc. The possibility of arcs with cathodes too cold for thermionic emission is being accepted. Application of the heat balance method of determining the proportion of current carried by electrons from the cathode does not agree with the thermionic theory of the cathode. (Compton, A. I. E. E. TRANS., 1927). In applying the heat balance method, the experimental results of Van Voorhis (*Phys. Rev.*) on the heat of neutralization of positive ions are important. The view that electrons are drawn from the cathode by very high electrostatic gradients maintained by space charges is being favored (Compton, Prince, A. I. E. E. TRANS., 1927). In this connection, however, Rosario (*Journ. of Frank. Inst.*) describes experiments casting doubt on the ability of electric fields, of the order of magnitude here postulated, to draw electrons from a cold cathode.

### SHORT-TIME PHENOMENA

The study of transients occurring on transmission lines, with the aid of the klydonograph and surge recorder, has been actively pursued during the past year. Although much valuable information has been obtained, yet it is becoming increasingly apparent that more information is needed with respect to the form of the transients than the Lichtenberg figures have given.

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[*] COMMITTEE ON ELECTROPHYSICS:

V. Karapetoff, Chairman,
O. E. Buckley, Vice-Chairman,
Carl Kinsley, Secretary.
V. Bush,
F. M. Clark,
W. D. Coolidge,
W. F. Davidson,
J. F. H. Douglas,
C. L. Fortescue,
A. Hund,
W. B. Kouwenhoven,
K. B. McEachron,
R. A. Millikan,
C. A. Nickle,
J. Slepian,
Irving B. Smith,
J. B. Whitehead.

*Liaison Representatives of American Physical Society*

W. F. G. Swann
A. P. Wills

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

The cathode ray oscillograph is the only device available which will give an oscillographic record of the volt-time relations of short-time transients. Norinder has applied the oscillograph to this work successfully. Additional work is being undertaken in this country so that valuable contributions along this line may be looked for in the next few years.

The study of lightning and of transients due to lightning still continues to occupy the interest of physicists and engineers. Several laboratories in different parts of the world are being equipped to study high-voltage transients. Crest voltages of over 3,000,000 volts have been reached. Spark-gap measurements, insulator flashover, strength of insulation, as in transformers, and the strength of wood poles, are some of the problems being actively studied.

Valuable research has been accomplished in connection with the protection of oil tanks and reservoirs against lightning strokes. Still more work is needed in order that the mechanism of the lightning discharge may be more fully understood. Some studies have been reported in which the mechanism of the breakdown of a sphere-gap and a needle-gap under transient conditions has been studied experimentally. (Torok, see above; Zinszer, *Phil. Mag.*, 1928). Additional research of this nature would be of great value.

### HIGH-VOLTAGE RESEARCH

Further study has been made during the past year of corona, using the cathode ray oscillograph. Valuable contributions with respect to the space charge of corona have been made. Last year marked the first 220,000 volt transmission to be installed in the East and this year this system has been considerably extended. Studies of lightning phenomena are being continued on this 220,000-volt system with the promise of obtaining useful data.

### FERROMAGNETISM

Among the advances which have been made in the field of ferromagnetism during the past year are the following:

1. Further studies of the magnetization and magnetostriction of single crystals of iron (Dussler and Gerlach) and of nickel (Kaya and Masiyama, and Sucksmith, Potter, and Broadway), show the dependence of these properties on crystallographic direction.

2. The permeability of iron has been reported in two papers (Wait, and Gutton and Mihul) to have no peculiarly small value in alternating fields of radio frequencies, contrary to the results of Wwedensky.

3. Magnetic viscosity, the time lag in magnetization, has been investigated experimentally by Lapp.

4. DeWaard in a mathematical treatment has attempted to account for ferromagnetic properties as dependent on crystal form and crystal lattice.

5. Some evidence has been obtained by X-ray analysis of films of iron in magnetic fields as to the ultimate nature of magnetism. T. D. Yensen, *Phys. Rev.*, Vol. 31, April 1928, p. 714.

6. An X-ray analysis of thin films of electrolytic iron gave results supporting the hypothesis of the atomic nature of magnetism. A circular X-ray diffraction pattern resulting from the randomly oriented minute crystals of iron in a film were examined with the film unmagnetized and also magnetized. No difference in the pattern due to magnetization could be detected, a result apparently explicable only on the assumption that the fundamental magnetic unit is atomic in character.

7. A notable contribution to the literature of ferromagnetism, of particular interest to electrical engineers, is T. F. Wall's book on Applied Magnetism.

8. A new method of obtaining strong magnetic fields has been described; P. Kapitza, *Roy. Soc. Proc.*, 115, Aug. 1927, p. 658.

9. A magnetic field within a coil of wire was produced by sending through the coil a current with amplitude in some cases as high as 72,000 amperes. As a source of current, a single-phase a-c. generator of the turbo alternator type was used, a half cycle only being utilized. A magnetic field within the coil, of about 320,000 gauss, was developed for about 1/100 of a sec. throughout a volume of 2 cu. cm. The chief difficulty encountered was in designing a coil to withstand the extremely large mechanical distorting forces of electrodynamic origin. Experiments on the change of resistance of bismuth due to a field of 300,000 gauss showed a thousandfold increase in resistance at the temperature of liquid air and a fiftyfold increase at room temperature.

### RADIO AND ELECTRO ACOUSTICS

The following were live topics during the year under review:

*A. Radio:*

1. Propagation phenomena; effect of solar activity, ionized regions, Heaviside layer, etc., on radio transmission;
2. Precision measurement of frequency;
3. Television without wires;
4. Radio on trains;
5. Miscellaneous apparatus, such as field intensity sets, tube generators, etc.

*B. Acoustic matters:*

1. Super-sonic waves in gases, liquids, and solids;*

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*By super-sonic waves are meant longitudinal vibrations similar to sound waves, but of frequencies much beyond the audible range, reaching as high as 400,000 oscillations per second and beyond. Some striking effects of such waves, as well as practical applications, have been demonstrated by Prof. R. W. Wood of Johns Hopkins University.

2. Analysis of vowel and other sounds by means of technical devices;
3. Bessel and exponential horns for sound power;
4. Loudspeaker and receiver tests;
5. Sound transmission through building materials.

*C. Generation of Sinusoidal Sound Waves:*

A beat-frequency generator, for producing audio currents which are practically sinusoidal, has been constructed by the Bureau of Standards. The frequency is adjustable and stabilized by means of a piezoelectric quartz disk and can be directly read off on a scale. The holder containing the piezoelectric element has a hand control for changing the frequency of the quartz disk by a small amount (a fraction of a cycle to several cycles).

On account of the piezoelectric control, it is possible to reset the calibration for the frequency for most any useful *B* voltage on the tubes producing the two high-frequency currents which beat with each other. The resetting can be carried on without any standard, by means of a filament rheostat common to both oscillator tubes. The slow visible vibrations on the meter for the anode current of the piezoelectric oscillator are utilized for the resetting of the scale.

A thermostatic control is provided for very accurate work. Two filter detector circuits are provided for obtaining audio currents of a good wave shape and keeping any high-frequency currents away from the load branch. A specially designed power amplifier is available. The same is used when more energy is required.

## MAGNETIC AND ELECTROSTATIC FIELDS

Magnetic field distribution has been studied in application to various problems in electrical machinery, such as reluctance, wave form of e. m. f., pole-face losses, inductance, armature reaction, etc.

An important advance in our knowledge of magnetic fields is the work of Dr. Th. Lehmann. In the *Revue Générale de l'Electricité*, Dec. 24, 1927, he discusses the effects of pole saturation and interpolar iron on interpolar flux, considering as before the non-lamellar character of the field. The non-lamellar field, also treated in some recent articles in the *General Electric Review*, and *Electric Journal*, is related to eddy-currents, which were considered by Roth, Schenkhag, and Strutt. Roth has discussed the case of slot-conductors in the *Revue Générale de l'Electricité* of Sept. 27, 1927. H. Schenkhag and M. Strutt have discussed the flux distribution in busbar conductors, in the *Archiv für Elektrotechnik*. Dr. E. Weber, in the *Archiv für Elektrotechnik* of Nov. 17, 1927, has reported on the effect of the pole-shoe shape on flux distribution and wave form of e. m. f. Dr. Th. Lehmann has pointed out a needed modification of the "Minimum-Reluctance Rule" in computing mechanical forces of the magnetic field.

The electrostatic field of force within high-tension transformers has been investigated by Dr. J. Labus in the *Archiv für Elektrotechnik* for Nov. 3rd, 1927. The method used was that of the functions of a complex variable, and several new cases have been solved. W. Wittwer in the *Archiv* for April 7, 1927, reported on a combined mathematical and experimental method, by which he has studied the correlation between the breakdown strength and the geometrical factor, for the cases of insulation bounded by electrodes with sharp edges.

## DIELECTRICS

In view of the existence of a Committee on Electrical Insulation of the National Research Council (Professor J. B. Whitehead, Chairman) with which the writer of the present report has kept in close touch through several members common to both committees, the activities of the Electrophysics Committee in the field of dielectrics so far have mainly consisted in cooperating with the other committee. Those interested in details of various research projects and actual investigations in the field of dielectrics, should consult the Annual Reports of the Committee on Electrical Insulation. Among the principal problems under discussion are the following: (a) Dielectric phase difference, loss and absorption; (b) Ionization, polarization, and physical theories; (c) Dielectric strength and breakdown; (d) Dielectric constant; (e) Resistivity and conductivity; (f) Flashover; (g) Physical and chemical changes due to electric stress; (h) Properties of particular materials as related to manufacturing processes; (i) Special problems on the insulation of communication systems.

At the summer convention of the A. I. E. E. in Detroit, in 1927, a serial report of the Committee on Electrical Insulation covered the literature on Electric Strength of Solid and Liquid Dielectrics. During the past year there have been few contributions on this subject in American literature and the foreign press has contained a few articles. Apparently more attention is being given to other phases of dielectric behavior and to consideration of various series of dielectric phenomena. A serial report of the Committee on Insulation of the National Research Council prepared by Dr. Curtis covers the subject of electrical resistivity of insulating materials, and we have had a paper on the Theory of Imperfect Solid Dielectrics by Dr. Malti. Bush and Moon have reported on a device for automatically obtaining a large number of determinations of dielectric strength as a means of eliminating some of the uncertainties due to the wide variations between individual readings. This seems to offer considerable promise if applied to other materials than those studied by these authors.

A paper by Murnaghan throws additional light on the Boltzmann-Hopkinson principle of superposition as applied to dielectrics and is indicative of the attention which is being given in several laboratories to the phenomenon of absorption.

A considerable number of thorough-going researches are under way dealing with various phases of impregnated paper insulation as used in high-voltage cables, and the results of some of these have appeared in print as papers before the Institute, or those of rather more restricted circulation. This includes the paper presented by the Detroit Edison Company before the Association of Edison Illuminating Companies.

Joffé, at Leningrad, and some of his coworkers are studying dielectric absorption in its relation to polarization and conductivity of crystals. This work is very significant in its indication of the nature of dielectric absorption in some of its manifestations. He shows that in certain crystals there is an initial constant conductivity and that the final absorption phenomenon is due to a polarization which may be treated independently of the conductivity. Some of his coworkers have attempted to show that this initial conductivity is sufficient to account for the dielectric loss.

A number of experimental researches on dielectrics is being conducted at various universities, as will be seen from the following partial list:

Harvard University, under Prof. C. L. Dawes—"Gaseous Ionization in Impregnated Paper Insulation."

Massachusetts Institute of Technology, under Prof. V. Bush—"The Properties of Papers used for Impregnated Paper Insulation."

Johns Hopkins University, under Prof. J. B. Whitehead—"Influence of Variations in Drying and Evacuating Processes on the Properties of Impregnated Paper."

University of Wisconsin, under Prof. Edward Bennett—"Relation between Dielectric Losses and Anomalous Charging Current."

University of Illinois, under Prof. E. B. Paine,—"Ionization in High-Voltage Cables."

The Johns Hopkins University, under Prof. W. B. Kouwenhoven,—"Phase Difference in Air Condensers."

University of Wisconsin, under Professor Edward Bennett,—"Properties of Dielectrics."

The Johns Hopkins University, under Prof. J. B. Whitehead,—"Fundamental Study of Dielectric Absorption of Waxes and Oils."

Cornell University, under Professor V. Karapetoff,—"Study of Oils used in High-Tension Cables."

These researches are supported for the most part by the National Electric Light Association, Association of Edison Illuminating Companies, the Engineering Foundation, or individual public utilities.

### MECHANICAL SOLUTIONS OF ENGINEERING PROBLEMS

An Integraph has been developed by Professor V. Bush and his coworkers at Massachusetts Institute of Technology, for a mechanical solution of rather complicated differential and integral equations occuring in various branches of engineering. The machine has already been applied to several problems; for details see *Journal of Franklin Institute*, Jan. 1927, p. 63, and Nov. 1927, p. 575; also *Physical Review*, Feb. 1927, p. 337.

A mechanical device which quantitatively imitates electric transients in an interconnected power system, was described in a paper by R. C. Bergvall and P. H. Robinson at the Baltimore Regional Convention of the A. I. E. E., (QUARTERLY TRANS., July 1928).

### TEMPERATURE MEASUREMENTS

On May 12, 1927, the following resolution was passed by the Standards Committee of the A. I. E. E.: "That the broad question of standards for the technique of temperature measurement be referred to the Electrophysics Committee for investigation and report." In accordance with this request, the chairman has taken steps to ascertain the views of some interested parties and obtained a list of persons competent to serve on a subcommittee on Temperature Measurements. The problem is quite broad and the proposed subcommittee will have to investigate various methods of accurate temperature measurement, used in practise and in scientific work, find out their limitations and advantages, and select those which are sufficiently accurate without being unduly intricate. The chairman of this subcommittee has not been chosen as yet, but the matter has been submitted to the Bureau of Standards in the hope that a member of their staff may serve as chairman and thus be an impartial connecting link among the various industrial groups and scientific specialists represented on the subcommittee. It may be of interest to mention that there is a Committee on Heat Transmission of the National Research Council, and among its subcommittees there is one on Temperature Measurements. It is hoped that the proposed subcommittee will cooperate with this subcommittee.

### SOME POINTS OF CONTACT BETWEEN ELECTROPHYSICS AND ELECTRICAL ENGINEERING

A pure physicist usually studies whatever interests him most, or for whatever problem he has the necessary experimental and mathematical equipment. On the other hand, an applied physicist, or an engineer working on the border line between engineering and physics, is naturally limited to those topics which promise a more or less immediate application. The following list indicates some of such topics, although undoubtedly there are many more not included in it. It is hoped that this list may stimulate some younger engineers to undertake further "importation" of methods and results from the domain of physics into that of engineering.

*Arcs;* their theory, spectroscopy, phenomena at the cathode, stability, range of voltage, distribution of potential.

*Atmospheric Electricity;* theories of; methods of measurement; prediction of disturbances; thunderstorms, aurora borealis, ionized conducting upper layer of the atmosphere, the nature of terrestrial magnetism.

*A-C. Bridges*; various types, sources of power, detectors, inaccuracies, shielding.

*Bushings for Extra-high Voltages;* theory of stress distribution; design, experimental investigation of stresses, and safety against flashovers.

*Cables;* capacitance, heating, insulation resistance, ionization, study of oil and paper, stresses, joints, sheath and armor.

*Capacitance;* computation of, for lines, cables, plates, spheres, antennas, and irregular shapes. Measurement of capacitance in difficult cases; design of condensers for extra-high voltages and large capacitance.

*Cathode Rays;* their theory, production, measurements, application to oscillograph, penetration through matter, production of X-rays.

*Circuits;* general theory of; Heaviside's operational calculus; Carson's theories.

*Conduction of Electricity* in gases, liquids, and solids; fundamental theories, crucial experiments.

*Contact Phenomena;* resistance, e. m. f., heating, etc.

*Corona,* as a particular case of ionization and conduction in gases; study of the individual layers of ionized gas, from the electrode out; space charge, mobilities of ions, etc.

*Dielectrics* (topics discussed above).

*Discharges;* glow, brush, streamers, sparkover; their spectroscopy; character of ionization, numerical relationships.

*Electromagnetic Theory;* circuit equations, propagation of disturbances in dielectrics, dispersion; vector calculus operators; eddy currents in large conductors.

*Electrometers;* uses, theory, improvements in construction to facilitate setting up and use.

*Electrons and Positive Ions;* the fundamental properties: mass, charge, velocity, equivalence to a current, magnetic and electrostatic fields produced by such ions; action of external fields on an ion; relativity correction for mass; statistical mechanics of ions and neutral particles of matter in a mixture; reflection, ionization, diffusion, mobility, space charge; clustering; different kinds of collisions; refraction from crystals.

*Fields, Electric and Magnetic;* theory of fields, mapping out a field experimentally; theoretical plotting of lines of force and of equipotential surfaces; extension to three-dimensional problems.

*Heat conduction* in electric conductors and in dielectrics; accurate measurement of temperature distribution in electrical apparatus; theoretical investigation of heat flow in connection with iron loss and dielectric loss.

*High-Voltage Tests;* development of the technique of impressing a voltage of desired magnitude and wave form (steady, sinusoidal, impulse, etc.) and of accurately measuring its effect.

*Inductance;* measurement and theoretical computation of, for coils, lines, cables, and conductors of irregular shapes; effect of frequency.

*Lichtenberg Figures;* a detailed study of their production and properties; development of more sensitive figures which would clearly differentiate between the magnitude of an impressed voltage and its wave form.

*Lightning Protection;* development of laboratory tests for lightning arresters under conditions approximating actual service; measurement of actual line disturbances; production of materials and combinations with a smaller time lag, for lightning arresters; valve action; effect of a resistance in series with a protective device.

*Measurements* of amplification, current, frequency, voltage, power, phase angle, resistance, inductance, capacitance, time intervals, lengths, etc., when these quantities are extremely small, extremely large, of transient nature, or have to be observed under difficult conditions. Measurement of quantities introduced by the modern electronic physics, such as ionic currents, quanta, radiations, spectral lines, photoelectric effects, etc.

*Oscillations;* generation of electric oscillations; suitable circuits; theory of complex oscillations; the matrix theory of spectral lines.

*Oscillographs;* further development of types to extend the present range of usefulness.

*Photoelectricity;* theory of; measurement of the quantities involved; development of better photoelectric cells; new applications of such cells.

*Piezoelectricity;* theory, applications, apparatus, measurements.

*Quantum Theory.* This theory is the foundation of modern physics, and one not familiar with its premises and formulas is cut off from reading most modern books and periodicals in physics and from following the progress of the art.

*Spark-Gaps and Sparkovers.* Much remains to be done in ascertaining the behavior under various conditions of gas pressure, temperature, and moisture. A more rational theory, in terms of electronic ionization, photoelectric effect, and space charge is also needed.

*Spectroscopy* is proving to be a very powerful tool in various physical studies, so that it is of importance for engineers to become familiar with its methods, theory, and nomenclature, such as band and line spectra, arc and spark spectra, relative intensities of lines, superfine structure, terms, series, excitation by collisions and by radiations, etc.

*Structure of Matter.* The present knowledge of intra-atomic phenomena is in most cases insufficient to account for the complex phenomena with which engineers are concerned, making an empirical approach unavoidable. Nevertheless, a rapid progress is being made in atomic physics, and new methods and concepts are being introduced, such as quanta, relativity, the matrix theory, the wave mechanics (Broglie-Schroedinger), etc., so that engineers working on the border-line of physics should keep posted at least on the general trend of the progress, introducing new concepts and terminology into their work as much as possible.

*Thermionics;* emission of electrons from hot bodies; theory and methods of measurement.

*Transient Phenomena;* although the theory of many transients has been thoroughly investigated, yet there are many others of greater complexity or of shorter duration, for which we have neither a satisfactory theory nor proper recording devices.

*Vacuum Technique.* More and more electrical measurements have to be performed in a high vacuum or under reduced pressure, and it is of importance to continue developing pumps, pressure gages, temperature and moisture control, elimination of impurities, etc., to make such measurements simpler and more accurate.

*Waves and Surges* along wires and in dielectrics acquire greater and greater importance both in power engineering and in communication work. Their experimental investigation is for the most part quite difficult, for they are transients in time and in space, whereas our recording devices are stationary and measure transients in time only. The theory of such transients is also quite involved and requires a knowledge of some new and advanced branches of mathematics and physics. Nevertheless, the electrical profession as a whole will have to develop experts capable of dealing with such problems, and a concerted effort should be made without further delay, possibly beginning with the best colleges of engineering.

*Wave Mechanics.* At the present writing, much of theoretical atomic physics is being re-written on the basis of the so-called "wave mechanics," introduced by de Broglie and Schroedinger. If this point of view continues to be successful, the next generation of engineers may have to deal with concepts entirely different from ours. Even such well-established principles as electronic orbits within an atom, begin to be looked upon as mere abstractions of the human mind rather than physical realities. For a general exposition of this theory see H. F. Biggs, "Wave Mechanics," *Oxford University Press*, 1927; K. K. Darrow, *The Bell System Technical Journal*, 1927, Vol. 6, p. 653; W. F. G. Swann, *Journal of Franklin Institute*, 1928, Vol. 205, pp. 323 and 519.

*X-Rays.* The importance of X-rays in various industries increases each year, so that many more electrical engineers should become familiar with the theory of these particular radiations, as well as with the handling of the apparatus and specimens. Moreover, X-rays are proving to be a powerful means of studying the structure of matter, and the constitution of the atom, particularly in its inner parts adjacent to the nucleus, which latter remains the least known part of the atom.

VLADIMIR KARAPETOFF, *Chairman.*

# High-Frequency Measurements

## ANNUAL REPORT OF THE COMMITTEE ON INSTRUMENTS AND MEASUREMENTS*

*To the Board of Directors:*

The Committee on Instruments and Measurements is at present studying several pertinent phases of electrical measurements through standing subcommittees as follows:

1. Measurements of Variable Power and Large Blocks of Energy
2. Dielectric Power Loss and Power-Factor Measurements
3. Measurement of Non-electrical Quantities by Electrical Means
4. High-Frequency Measurements
5. Remote Metering

The present status of these is as follows:

### VARIABLE POWER AND LARGE BLOCKS OF ENERGY

This subject was covered in the report of the committee for 1925-26. Additional matter for future report is being collected by the subcommittee under the chairmanship of Mr. T. E. Penard.

### DIELECTRIC POWER LOSS AND POWER FACTOR

This subject was covered by symposium at the Niagara Falls Regional Meeting of the Northeastern District, May 1926. Additional matter is submitted in the following report by Mr. H. Koenig, subcommittee chairman.

In May 1926, a symposium on dielectric loss and power factor measurements was held at Niagara Falls. The symposium was called for the purpose of recording the then well-known methods of taking such measurements, probably as the first step toward standardizing such tests.

It is a difficult matter, of course, to determine just how effective the symposium was. It was the feeling of those who presented papers describing the various methods of making dielectric loss and power factor measurements that there was little hope of standardizing on any one method. The symposium did serve, however, to clear the atmosphere about these measurements and to point out the advantages and disadvantages of each method. It was also indicated at that time that a scheme for calibrating and checking the various methods now in use would be of great advantage.

Since the symposium, there have been two known advances in the line of checking dielectric loss equipments, particularly in the tests of underground cable. The first is the calorimeter method which was brought out in the discussion at the symposium by Mr. E. S. Lee of the General Electric Company. The second is the use of standard loads which have been developed at the Electrical Testing Laboratories. To the best of my knowledge, the only checking by the calorimeter method has been done by the General Electric Company in their own laboratories. A paper entitled *A Thermal Method of Standardizing Dielectric Power Loss Measuring Equipment*, by Messrs. J. A. Scott, H. W. Bousman, and R. R. Benedict, (A. I. E. E. QUARTERLY TRANS., July 1928) was presented at the Baltimore Regional Meeting of the Middle Atlantic District, April 1928, describing further comparisons using this method.

During the spring of last year a set of standard loads developed at the Electrical Testing Laboratories was used in an intercheck covering ten cable factories in the eastern part of the country. The result of this intercomparison was very satisfactory. It is hoped that some time in the near future a paper covering the tests will be written.

All other developments have been along the line of improving the technique of making measurements rather than the introduction of new circuits or methods. Neither has there been any further effort along the lines of standardizing on the method of testing.

Numerous articles have been published in some of the foreign technical magazines covering dielectric loss and power factor measurements. No new methods have been suggested nor have radical changes been made in the methods in use in this country.

The importance of proper shielding in making dielectric power loss measurements is becoming more generally realized. A paper presented by C. L. Kasson at the Pittsfield Regional Meeting of the Northeastern District, May 1927, entitled *High-Voltage Measurements on Cables and Insulators*,[1] emphasized the necessity of proper shielding. The subcommittee is planning to hold a symposium on this subject in the spring of 1929 dealing with the general subject of shielding both in dielectric power loss and other measurements.

### NON-ELECTRICAL QUANTITIES BY ELECTRICAL MEANS

This subject was reported in a paper by P. A. Borden published in the TRANSACTIONS of the A. I. E. E., Vol. XLIV (1925), p. 238, together with an accompanying bibliography. The compilation of the bibliography has been continued by Mr. Borden, a second supplement having been published with the report of the Committee on Instruments and Measurements for

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***COMMITTEE ON INSTRUMENTS AND MEASUREMENTS:**

**Everett S. Lee, Chairman.**

**O. J. Bliss,**
**P. A. Borden,**
**W. M. Bradshaw,**
**H. B. Brooks,**
**A. L. Cook,**
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**T. E. Penard,**
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**G. A. Sawin,**
**R. W. Sorensen,**
**H. M. Turner.**

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

[1] A. I. E. E. TRANS., Vol. XLVI, 1927, p. 635.

1926-27. A third supplement of the bibliography is attached to this report.

A study of the range of subjects in this bibliography shows the ever-increasing extension of the measurement of non-electrical quantities by electrical means. The number of the articles being published at present on this subject is too extensive for Mr. Borden to continue their compilation. Instead, a series of papers or lectures on the various subjects involved will be presented before the Institute. The lecture by Dr. C. A. Heiland on "Geophysical Methods of Prospecting" given at the Summer Convention, Denver 1928, is the first of this series.

### High Frequency Measurements

This subject was thoroughly treated in a symposium at the Pittsfield Regional Meeting of the Northeastern District, May 1927, a résumé of which was given in the report of the Committee on Instruments and Measurements for 1926-27. Due to the wide interest in this subject and the rapid change in technique it was thought desirable to have a member act as liaison officer with the I. R. E. Committee on the Determination of Circuit Constants. The I. R. E. Committee has prepared a list of references containing the various types of measurement and in addition has developed new methods particularly with reference to the measurement of inductance of several hundred henries such as found in audio frequency transformers and choke coils both with and without superposed direct current. The report of this work is to be published. Professor H. M. Turner, subcommittee chairman, has been active in this work.

### Remote Metering

The following report prepared by Mr. E. J. Rutan, subcommittee chairman, gives the results of answers to questionnaires relative to the present status of this subject.

The Instrument and Measurements Committee sent out questionnaires for the purpose of obtaining information on remote metering equipment now in use. These questionnaires were sent to a number of representative electric power companies, railroads, manufacturers, and public utility holding companies located both in this country and in Canada. From a total of 108 inquiries, 76 replies have been received as listed in Table I:

TABLE I

| Group | Classification | Number of Replies |
|---|---|---|
| A | Electrical Transmission of Electrical Measurements | 31 |
| B | Electrical Transmission of Mechanical Measurements | 10 |
| C | Remote Metering Equipment in Use, no Data Given | 3 |
| D | Prospective Users of Remote Metering Equipment | 6 |
| E | No Remote Metering Equipment in Use | 26 |
| | Total | 76 |

The purely electrical remote metering systems, as reported in the replies in group "A," can be classified into the ten distinct systems given in Table II.

TABLE II

Classification of Remote Metering Systems

| | | | |
|---|---|---|---|
| 1. | Voltage | 6. | Potentiometer |
| 2. | Impulse | 7. | Frequency |
| 3. | Position (induction) | 8. | Impulse Condenser |
| 4. | Inverse Current | 9. | Contact Integration |
| 5. | Current | 10. | Thermal Converter |

Referring to a paper on the *Automatic Transmission of Power Readings*, by B. H. Smith and R. T. Pierce, presented at the Midwinter Convention in Philadelphia, February 1924, it will be noted that the first seven types of systems listed in Table II were described in that paper. In the discussion that followed, the thermal converter type was also mentioned. The two systems not mentioned in the paper are not necessarily new. The contact integration system was mentioned in five replies and the impulse condenser was mentioned in two replies. Judging from the replies to the questionnaires, no new fundamental remote metering devices or systems have been developed since the presentation of the paper by Messrs. Smith and Pierce. The systems described in that paper will be given only a brief general description here but the other three systems will be described more in detail.

An attempt has been made to give an idea of the characteristics of operation and the accuracy of each method as it was reported. This was done in spite of the fact that nearly all of the users of remote metering equipment were compelled to report the performance of their systems under widely varying conditions. Certain systems whose inherent characteristics render them inaccurate due to interference from outside sources, can be made more reliable by the proper installation and shielding of the transmission line. It may also be noted that while the transmitter is often sufficiently accurate the receiver chosen to operate with it necessarily limits the accuracy of the system. This may cause the reported accuracy to be low, while a more accurate receiver would result in a more favorable reply. The importance of this point is evident when it is realized that many systems are classified according to the type of transmitter used without reference to the type of receiver. It is evident, then, that more definite information is needed to reconcile many of the apparently contradictory replies.

No attempt has been made to summarize the first cost and maintenance as no definite figures were given, and the replies received were evidently based upon the correspondent's limited knowledge of only a few of the systems in use.

*1. Voltage.* In this system the voltage supplied to the receiver is varied by a potentiometer which is operated by an instrument measuring the quantity desired. Some types are varied by a Kelvin balance or relay type graphic meter. The indications are transmitted over supervising wires, pilot wires, or pressure wires to a voltmeter type indicating or graphic meter.

The chief advantage of this system is its simplicity. Obvious disadvantages are its sensitiveness to changes in line resistance and the necessity for close regulation of the supply voltage.

A few companies reported the reading of voltage directly over distances from a few hundred feet to two miles.

*2. Impulse.* This method seems limited to watthour type meters in which impulses proportional to the speed of the meter are sent out to receivers where polarized relays actuate an escapement. Dials geared to the escapement record the power being measured.

This method has the advantage of being positive in its action and quite independent of line conditions. The distance over which this system may be used seems to have no definite limit, the greatest reported distance being 200 miles. Some disadvantages are the intricate type of receiver necessary, a delicate transmitter which is likely to introduce errors, and the possibility of being affected by static disturbances. The reported accuracy seems to range from "fair" to plus or minus one per cent of full scale deflection.

*3. Position.* This method employs two similar a-c. induction motor units in which the rotor of the receiver closely follows the movements of the rotor of the transmitter.

This system is very simple and requires little or no attention. It is also very reliable, positive in action, and comparatively independent of line conditions. The line resistance limits the distance over which operation is possible, the limiting resistance being about 3000 ohms.

This method has the disadvantage of requiring five wires for operation. It is also reported that the transmitter needs a powerful operating torque, thus making it necessary to use more powerful instruments. It is sometimes necessary where a number of large receivers is connected together, to make use of power amplifying relays and motors.

The reported accuracy of this system as given by one manufacturer is two per cent of full scale deflection.

*4. Inverse Current.* This method makes use of a motor operated rheostat, controlled by the indicating or recording meter, which simultaneously adjusts the circuit resistance and the counter torque on the instrument. The receiver is a recording or indicating ammeter which receives current inversely proportional to the load.

An outstanding advantage of this method is the ease with which any number of indications may be totalized by connecting the rheostats of each meter in series. The resultant current is then inversely proportional to the total load.

The chief disadvantage lies in the complicated design and wiring necessary. The precision is also reported as being low or only fair.

*5. Current Balance.* This method is similar to the inverse current method except that the rheostat is connected to a Kelvin balance type of meter and the resultant current is directly proportional to the load. The receiver may be an inverted transmitter or an indicating or recording ammeter.

These instruments may be placed in parallel and the totalized current is then proportional to the total load. This method seems quite widely used, 9 replies reporting satisfactory operation of this system. One manufacturer reported 31 users of this system, 5 of whom replied to the questionnaire. Seven users of method reported transmission distances of at least 3 mi. and up to 24 mi.

The accuracy appears to be good, some stating that it depends on the choice of a receiver.

*6. Potentiometer.* The potentiometer type may also consist of a Kelvin balance type meter which controls a motor operated rheostat, but in this case it is the line voltage which is varied. The receiver may consist of motor operated rheostat controlled by a contact making voltmeter; or as reported in one letter, a milliammeter is used.

One of the advantages of this system is that the calibration is not materially affected by a change of line resistance. Another advantage is that a telephone line may be used for transmission. This method was reported in use on lines up to 56 mi. in length. The accuracy is reported as "fair" and probably depends on the choice of equipment.

*7. Frequency.* This is a complex system in which a Kelvin balance type of meter is made to control the frequency of a small a-c. generator. At the receiving end a frequency meter is used, calibrated to read load power. This system is easily adapted to totalize any number of readings. The control of apparatus may also be effected.

This system does not seem suitable for customer installation due to its complex nature, involving as it does elaborate apparatus and requiring constant attention. When used by a company that uses and distributes large blocks of power over considerable distances, the excellent results that are obtained would seem to warrant its installation.

*8. Impulse Condenser.* In this novel system, contacts on several meters are momentarily made to connect a condenser to a charging circuit, and the receiving instruments perform a measurement upon the rate of discharge of this condenser through a resistance. This system was used over lines 3½ mi. long.

The accuracy of this system seems to be low. The information received for this method is meager, but little seems to be said in its favor.

*9. Contact Integration.* This system may consist of contacts operated by a watthour meter, wherein the total number of contacts made over the system is totalized on a recording instrument, or the contacts made by demand meters are recorded at one point on one instrument. The greatest reported distance of transmission was 5 mi., but this range may be extended by the use of suitable relays.

The accuracy of this method seems to depend upon the type of transmitters and receivers and the amount of local interference. Accuracies from one to two and one-half per cent were reported.

This system apparently gave satisfactory service in four out of five reported cases, while the fifth correspondent reported a failure due to induction from a nearby high-voltage line.

*10. Thermal Converter.* The important unit in this system is known as a thermal converter, and consists of two heating elements so connected to the instrument current and potential transformers that the temperature difference of the two elements is proportional to the watts in the metered circuit. Thermocouples are placed in this converter in such a manner that the "hot" junctions are associated with one heating element and the cold junctions with the other. The resultant thermoelectric potential is proportional to the difference in temperature of the two heating elements and is therefore porportional to the watts or power in the circuit. It was found possible to design the thermal converters to give a linear characteristic over the range used, and thus allow the units to be connected in series, when it is desired to totalize loads from a number of sources.

The accuracy of this method seems to lie in the receiver, which is usually a high-grade recording potentiometer, when accuracy may be of the order of one-half of one per cent. Thus a null method of measurement is used which practically eliminates any possible effect due to changes in line resistance. Indications have been transmitted successfully up to 8 mi. over telephone and supervisory lines. Other reported advantages are the lack of moving parts in the transmitting unit and the complete reversibility of the converters. This latter feature permits the use of this method on tie feeders where a reverse of power may occur.

This is the only new type of system developed since 1922 which has come to the attention of the committee. Arrangements are being made for the presentation of a description of this system before the Institute.

### CONCLUSION

It is still the feeling of the subcommittee that sufficient operational data have not yet been submitted to allow conclusions to be drawn as to the accuracy of the remote metering systems in use.

### ADDITIONAL SUBJECTS

In addition to the work being carried on by the standing subcommittees as reported above, there are several other subjects which the committee are working upon as the following:

### SYSTEM DISTURBANCES

There is a growing demand for recording instruments for switchboard application to record the variation of current, voltage, and power with time during system disturbances. In this connection a symposium was held jointly by the Committee on Protective Devices and the Committee on Instruments and Measurements at the New Haven Regional Meeting of the Northeastern District, May 1928, at which time two series of papers were presented, one describing available instruments for making these measurements and the other giving the experiences of the operators in the use of these instruments. This symposium was under the direction of Mr. R. T. Pierce for the Committee on Instruments and Measurements. The papers presented under the auspices of this committee were:

*Hall High-Speed Recorder*, by C. I. Hall*

*Pages from the Hall High-Speed Recorder*, by E. M. Tingley†

*Oscillograph Recording of Transmission Line Disturbances*, by J. W. Legg†

*High-Speed Graphic Voltmeter*, by A. F. Hamdi and H. D. Braley.*

### REVISION OF ELECTRICAL UNITS

Following the presentation by Dr. E. C. Crittenden at the Summer Convention of the Institute, Detroit, 1927, of a paper entitled *The International Electrical Units*, a resolution was presented and passed that the matter of the revision of the electrical units should be referred to the Committee on Instruments and Measurements for their consideration and study. This has been done and resolutions have been prepared and transmitted to the Board of Directors through the Standards Committee, urging the United States Bureau of Standards and other foreign national standardizing laboratories to undertake the necessary researches to eliminate the present discrepancies between the legally established electrical units and the absolute units which they were intended to represent, and to urge the legalization of absolute units.

### MEASUREMENT OF CORE LOSSES IN TERMS OF SINE-WAVE CORE LOSSES

The Committee on Instruments and Measurements has been asked to investigate and report on the best way to make core loss measurements so that they will give accurate sine-wave core losses regardless of the wave form employed for excitation. This subject is being studied by a working committee under the chairmanship of Mr. W. M. Bradshaw.

### DISTORTION FACTOR—DEFINITION AND METHOD OF MEASUREMENT

The Committee on Instruments and Measurements has been asked to give consideration to the adoption of a definition for distortion factor and methods of test, as disclosed in a report of the French Electrotechnical Commission entitled "Methods of Determining the Distortion of the Voltage Wave of Alternators." This matter is being considered by a working committee under the chairmanship of Mr. W. M. Bradshaw.

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*A. I. E. E. QUARTERLY TRANS., Vol. 47, No. 1, Jan. 1928.

†A. I. E. E. QUARTERLY TRANS., Vol. 47, No. 4, Oct. 1928.

### ACKNOWLEDGMENT

It is but fitting that we recall at this time the contribution in the past to the work and activities of this committee by Mr. J. R. Craighead. Mr. Craighead was appointed Chairman of the Instruments and Measurements Committee at the beginning of this year but he was removed from us by sudden death November 22, 1927. In his passing there have been lost to us the contributions of an active and energetic worker, and the advice and counsel of a scholar.

EVERETT S. LEE, *Chairman.*

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# Electrical Communication

## ANNUAL REPORT OF COMMITTEE ON COMMUNICATION[*]

*To the Board of Directors:*

The Committee on Communication submits the following report as a summary of the progress which has been made in the electrical communication art during the past year.

### PRINTING TELEGRAPHS

There has been continued growth in the use of printing telegraph instruments. In addition to the applications for police service mentioned under another heading, the volume of commercial message and similar traffic handled by such instruments shows a steady gain, both on long and short circuits. As an example of the latter, it may be noted that more than 800 circuits connecting main and branch officers of the telegraph companies are now equipped with printers.

The tendency to reduce manual operations as much as practicable has been quite pronounced in ocean cable telegraphy during recent years. As a result, printing telegraph equipment is now employed on both long and short cables in many cases. Recent developments in this direction were described in a paper entitled *Printing Telegraphs on Ocean Cables* which was presented by H. Angel at the 1927 Summer Convention of the Institute.

The automatic tape transmission system for telegraph tickers which was mentioned in the 1926 and 1927 reports has been further extended during the past year, so that full market quotations are now available to practically all sections of the United States.

### TELEGRAPH REPEATERS

Many of the repeaters now used on long telegraph circuits, both in land line and ocean cable service, are of the regenerative class. In such repeaters, automatic means are employed to retransmit practically perfect signals although the received signals may be so badly distorted that with earlier forms of repeaters the retransmission would be far from perfect. A description of one type of regenerative repeater and an outline of operating experience with it was given in A. F. Connery's paper on *A Non-Rotary Regenerative Telegraph Repeater* presented at the 1927 Summer Convention.

Rather important advances have been made in the simplification of circuit and equipment arrangements for telegraph repeaters installed in central telegraph offices.

### TELEGRAPH TRANSMISSION THEORY

A paper entitled, *Certain Topics in Telegraph Transmission Theory* was presented at the Winter Convention of the Institute by H. Nyquist. In addition to presenting a quantitative statement of certain fundamental telegraph requirements, this paper presented for the first time an analysis of the fundamental problems involved in single sideband carrier telegraph transmission which may offer important economies in frequency range under some conditions.

### CORD CARRIERS FOR TELEGRAMS

For some years past, most large telegraph offices have been equipped with mechanical conveyors, usually of the moving belt class, for the transfer of telegrams from one part of the operating room to another. A multiple cord carrier system has recently been developed which is proving very satisfactory for such conveying service. Where delivery to two or more points is necessary, the cord carrier equipment costs much less than the equivalent flat belt equipment. The power required to operate a three-channel cord system is no greater than that needed by a single-channel flat belt. Other advantages of the cord equipment are increased speed, reduced maintenance expense, minimum interference with lighting, and complete visibility at all points, thus facilitating inspection.

### DIAL TELEPHONY

The rapid application of dial telephone systems has continued. During the year, about 500,000 dial telephone stations were installed, bringing the total in service in this country, as of the first of January 1928, to approximately 2,900,000 stations or about 16 per cent of the total telephones in service.

A paper entitled *Some Recent Developments in Dial Systems*, by W. E. Farnham and H. M. Bascom, was presented at the Student Branch Convention and Sectional Meeting in New York in April of this year.

The dial system of operation has been extended to service from one suburban point to another suburb of the same city. This matter was discussed in a paper entitled, *Tandem System of Handling Toll Calls in and About Los Angeles*, by E. Jacobsen and F. D. Wheelock, which was presented at the 1927 Pacific Coast Convention.

### TOLL TELEPHONE SERVICE

During the year, telephone toll service was established between the United States and a number of important cities in Mexico, including Mexico City, Tampico,

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*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

Monterey, Saltillo, San Luis Potosi, Puebla, and others. The service was inaugurated by an exchange of greetings between President Coolidge and President Calles at the capital cities of the two republics over a circuit 3360 mi. long. The service from Mexican points was further extended to points in Canada by the end of 1927.

The various connections of the United States telephone network to important cities in Canada were augmented during the year by the completion of a circuit from Bismarck, North Dakota, to Regina, the capital of Saskatchewan.

A substantial improvement was made in the handling of toll calls, especially by increasing the percentage which are handled while the subscriber remains at the telephone.

### TELEPHONE TOLL CABLES

The extension of the network of toll telephone cables throughout the country continued at an increased rate during the year 1927, about 2000 mi. of cable being installed. Important additions included the completion of a route from Albany to Cleveland through Syracuse, Rochester, and Buffalo; the extension of the cable south of Washington to Petersburg, Virginia; and an extension from Chicago to Terre Haute, Indiana. In addition, a toll cable between Buffalo and Hamilton is approaching completion and another between Toronto and Oshawa is being started. This supplements the existing Toronto-Hamilton cable and provides a connection between the toll cable system in Canada and the great system in the United States.

At the present time, 7,500,000 telephones of the Bell System have direct access to the toll cable network in the northern and eastern parts of the country which provides within that area toll service which is relatively immune from the effects of storms.

### PLANNING EXTENSIONS TO TELEPHONE PLANT

The problems involved in the planning of telephone plant and descriptions of the telephone plant in various regions were discussed in a number of papers presented at Institute meetings. The principal papers were as follows: *Advance Planning of the Telephone Toll Plant*, by J. N. Chamberlain, presented at the Pacific Coast Convention; *Telephone Toll Plant in the Chicago Region*, by Burke Smith and G. B. West, presented at the Chicago Regional Convention; and *Planning Telephone Exchange Plants*, by W. B. Stephenson, presented at the St. Louis Regional Meeting.

### COMMUNICATION APPARATUS AND MATERIALS

The application of permalloy to communication problems continued during the year. Interesting information regarding this material was given in a paper entitled, *Manufacture and Magnetic Properties of Compressed Powdered Permalloy*, by W. J. Shackleton and I. G. Barber, which was presented at the Winter Convention.

A paper entitled, *Recent Developments in the Process of Manufacturing Lead-Covered Telephone Cable*, by C. D. Hart, was presented at the Chicago Regional Meeting.

### ELECTRICAL TRANSMISSION OF PICTURES

While no new stations have been added to the telephotography network of the Bell System (Boston, New York, Atlanta, Cleveland, St. Louis, San Francisco, and Los Angeles), interest in the service is increasing greatly and it is becoming much more important to the press.

### TELEVISION

At the last annual meeting in New York a talk on television was given by Dr. H. E. Ives, followed by a demonstration at the Bell Telephone Laboratories. A symposium on television at the Detroit Summer Convention was led by Dr. Ives and also was followed by demonstrations. The symposium included notable papers entitled: *The Production and Utilization of Television Signals*, by F. Gray, J. W. Horton, and R. C. Mathes; *Synchronization of Television*, by H. M. Stoller and E. R. Morton; *Wire Transmission of Television*, by D. K. Gannett and E. I. Green, and *Radio Transmission of Television*, by E. L. Nelson.

### CARRIER-CURRENT AND SUPERIMPOSED SYSTEMS

During the year there was a marked increase in the use of carrier-current systems in commercial telephone and telegraph plant, including a new system of a simplified nature which provides a single channel and is applicable economically to distances as short as 75 mi. The total length of carrier telephone circuits added during the year was approximately 65,000 channel mi.

In the application of carrier telegraph arrangements over 125,000 two-way channel miles were added to the Bell System during the year. This includes channels obtained from open-wire facilities by carrier frequencies above the voice range as well as voice-frequency carrier telegraph channels obtained from circuits in long toll cables. The increase is approximately evenly divided between the two types.

The application of carrier-current telephony to communication over power lines has increased steadily until, at the present time, there are in this country alone, 298 fixed stations in operation. Recent improvements in these systems have been along the lines of interconnecting them with private telephone systems. Portable and semi-portable carrier communication apparatus is being successfully used in conjunction with fixed stations. The large majority of these installations provide duplex operation, each system on a single frequency. The transmitter output is in the order of 50 watts, in the majority of the fixed installations; this power is proving adequate for usual conditions. As the demands for increased channels are made, the need of reducing the width of the communication channel without sacrificing understandability becomes more imperative.

Utilization of carrier current for other than communication purposes is rapidly increasing. The applications are for control of street lights, pilot protection of transmission circuits, supervisory control of substations and similar equipment, telemetering, etc.

Certain power companies are now using devices to operate graphic indicating meters at a distance, by means of d-c. impulses carried over signal circuits. By this arrangement, an operating supervisor or system operator may see at any moment the amount of power that is being fed into the system from generating points located at various places in the area covered by the power system. The total load taken by a town or city at some point may also be recorded at the system operating center.

Some recent developments in carrier current and other superimposed systems were described in the following papers presented at Institute meetings during the year:

*The Use of High Frequency Currents for Control,* by C. A. Boddie, Summer Convention 1927.

*A Carrier-Current Pilot System of Transmission Line Protection,* by A. S. Fitzgerald, Pacific Coast Convention 1927.

*Coupling Capacitors for Carrier-Current Applications,* by T. A. E. Belt, Pacific Coast Convention, 1927.

### SUPERVISORY CONTROL APPARATUS

In the power field, elaborate supervisory and control arrangements are now available by which an operator can control switches or other apparatus at distant points, and by means of currents transmitted back from the distant point determine the conditions which exist there. The Westinghouse Company reports that development work is being started on a form of such supervisory control apparatus, which is of interest in the communication field as it is intended to operate at frequencies in the voice range which can be transmitted over telephone circuits. The work has not yet reached the point where the possibilities and limitations of the system can be determined. Demonstrations of a preliminary model of the apparatus under the name "Televox" have, however, created considerable popular interest from the fact that the operation of such an arrangement over telephone circuits can be thought of as simulating conversation between persons.

### TRANSATLANTIC RADIO TELEPHONY

The opening of transatlantic telephone service between the United States and England was covered in last year's report. The service was improved by the completion of a radio receiving station at Cupar, Scotland, which is located as far north as conveniently possible for the purpose of reducing interference caused by atmospheric disturbances.

The time during which service normally is available has now been extended to 14½ hr., the period of service extending from 5.30 a. m. to 8.00 p. m., eastern standard time. The service was extended to Cuba and to five cities in Canada as well as to various cities of Continental Europe.

The outstanding event which took place during the period covered by this report was the holding of a joint meeting of two organizations on opposite sides of the Atlantic for the first time in history. This was a joint meeting of the Institute during the Winter Convention in New York with the British Institution of Electrical Engineers in London.

Preliminary to the joint session, a paper entitled, *Transatlantic Telephony—The Technical Problem,* was presented by O. B. Blackwell, and a paper entitled, *Transatlantic Telephony—The Operating Problem,* was presented by K. W. Waterson.

The joint session was preceded by the opening of communication from New York by Mr. Charlesworth who spoke to Colonel Lee in London. The telephone was then turned over to President Gherardi and to President Page of the British Institution of Electrical Engineers. After an exchange of greetings, brief addresses were given by Dr. F. B. Jewett and General John J. Carty from this side of the water and by Colonel Purves and Sir Oliver Lodge from London.

At various times during the year the transatlantic telephone service was discussed at a number of sectional meetings.

### INTERNATIONAL RADIO CONFERENCE

The International Radio-Telegraph Conference held in Washington in 1927 achieved several very important agreements affecting international radio communication. The delegates were faced with the responsibility of expanding an agreement made several years ago, mainly with a view to facilitating the use of radio in marine communication service. Since that agreement had been written, the use of radio had expanded to telephone as well as telegraph service and the field had widened to embrace in addition to the marine communication services, aids to navigation such as compass and beacon, aircraft and other new mobile services, point-to-point services, amateur and experimental work, and broadcasting. The new agreement had to apply to this much wider field of use without hampering the progress and development of the art. The most important achievements were the following:

The agreement on the assignment of frequency bands for services in the whole radio spectrum.

The recognition of the fact that every type or method of transmission of necessity occupies a definite frequency band or channel.

The agreement that interference to other services is the controlling limitation put upon the method of using a frequency channel.

The recognition of the amateur status in the international communication field.

The progressive suppression of the use of damped waves. No new installations using damped waves may be set up for land and fixed stations and the use of such waves at existing stations is forbidden after January 1, 1935. On ship and aircraft stations, new damped wave installations may be made only if such apparatus uses less than 300 watts on full power, and the operation of these damped wave installations is forbidden after January 1, 1940. Thus in 12 years the history of damped waves will close.

The agreement upon the use of an automatic alarm signal in the marine service.

The setting up of an International Technical Consulting Committee.

### RADIO BROADCASTING

Comparisons of results obtained by operating a broadcasting station with power outputs up to 100 kw. have established, fairly definitely, the essentials of this important subject.

Of considerable importance in connection with the performance of a high-power broadcasting station is the choice of site. Some locations are appreciably better than others, which indicates need of careful investigations before choosing a site.

Utilizing high-power tubes which recently became available, a 100-kw. transmitter has been developed which combines the essentials of all modern practises.

Since the previous report of this committee was made, two commercial 50-kw. broadcasting stations have been placed in operation.

Short-wave broadcasting and re-broadcasting in the U. S. and foreign countries has developed gradually with considerable recent improvements. These are mainly due to the utilization of sufficient power to provide dependable service and to improvements in the reception of short waves which have been almost exclusively used for this purpose.

Recent demonstrations of transmissions and receptions of both still pictures (facsimile) and moving objects (television), utilizing broadcasting transmitters, have indicated the probable future extensive application of these features to the present broadcasting service.

### OTHER RADIO COMMUNICATION

During 1927 short wavelengths were first utilized to provide a commercial service designed to maintain contact between the home office and ships making around-the-world tours. Such a service was applied also to ships plying between the United States and the far East where the distances are very great.

The percentage of long distance communication handled by short waves increased further during 1927. In the United States there were installed on several long distance radio circuits, the Radio Corporation of America's projector system. This system has been in use a sufficiently long period to demonstrate that it is a large factor in making it possible to obtain an economical long distance radio communication service. This projector system includes not only directive transmission but also directive reception. The directive reception differs from the transmission in that several receiving antennas directive in themselves, are spaced in such a manner as to eliminate the momentary fading which previously had so limited the use of short waves. With this method of receiving short waves it is possible to obtain a record so free from mutilation as to be practically perfect. Thus, in a way not anticipated some years ago, there has been accomplished the elimination of the effect of static.

The development and application of radio transmissions to aid in guiding aircraft has made rapid progress during the year.

Railroad train radio telephone equipment has been developed for front-to-rear communication on long freight trains. The apparatus provides telephonic communication and call signals between the locomotive and the caboose under all conditions whether the train is standing or in motion, and even when the train is broken if the separation does not exceed four or five miles. A four months test of the equipment was recently successfully completed on the James River Division of the Chesapeake and Ohio Railroad.

For cases in which the expense of the above mentioned telephone system cannot be justified, a signal system of lower power has been developed for service between front and rear of long freight trains. It provides only for call signals and telephonic communication is not possible. In operation a cord similar to a whistle cord is pulled, and a loud high-pitched signal is produced at the opposite end of the train. The range of this system is not over four miles.

Radio telephone equipment for railroad hump-yard service has been developed to facilitate the classification of freight cars at congested terminal points. The apparatus is similar to the train radio-telephone equipment, except that it is of lower power. The apparatus provides one way telephonic communication between the yard-master's office and any locomotive in the yards. The apparatus is operated the same as any telephone, and its range is limited to about two miles.

### SOUND REPRODUCTION

Improvements were made in the design of loudspeakers as regards efficiency, power, and uniformity over the speech frequency range. Some of the advances in design by which these improvements have been obtained were discussed in a paper entitled, *Loud Speakers of High Efficiency and Load Capacity*, by C. R. Hanna, presented at the Winter Convention, (A. I. E. E. Quarterly TRANS., Vol. 47, April 1928) and in a paper entitled, "A High Efficiency Receiver for a Horn-Type Loudspeaker of Large Power Capacity," by E. C. Wente and A. L. Thuras which was published in the *Bell System Technical Journal* for January 1928.

A paper entitled, *Electrical Reproduction from Phonograph Records*, by E. W. Kellogg, presented at the Detroit Summer Convention, discussed some interesting mechanical and electrical problems encountered in the development of improved reproducing devices.

### FIRE AND POLICE SIGNAL SYSTEMS

Further refinements of apparatus have been introduced in fire alarm systems during the past year. Improved automatic repeaters have recently come into use, the operation of which closely accords with the rules of the National Fire Protection Association requiring complete non-interference between coincidental signals, so that succession devices in street boxes will function, whether the boxes are on the same or on different circuits of the system.

In a new type of puncturing register the paper punchings are folded under instead of being detached, thus eliminating much objectionable paper dust; the instrument requires less power for its operation and runs at a higher speed than earlier registers.

Another improvement is the use of radio for communicating from fire alarm headquarters to moving apparatus, such as fire chiefs automobiles or fire boats. Boston has had such a broadcasting station for the past two years. It operates on a short wave, and has been found highly effective in sending orders to fire boats when absent from their regular berths. New York has recently experimented with a similar system.

In police signaling, an important development is the increasing use of telautographs and telegraph printers for interstation communication. These systems have been found useful in quickly and accurately spreading the news of hold-ups, automobile thefts, and other crimes. They have been found especially valuable where used in connection with the flashlight system of calling the patrolmen to the street signal boxes. A rather extensive installation of printing telegraph instruments made during the past year for the New York Police Department illustrates the expansion of service of this character. This system is so arranged that an operator at headquarters may send signals from a keyboard to any one precinct, to any group, or simultaneously to all precincts, the messages being printed automatically in page form at receiving machines placed close to the desks of officers in charge of precincts. Facilities are provided so that the receipt of the message may be acknowledged by each station. Another interesting system of this kind is in Connecticut, where police headquarters in twelve important cities are interconnected by telegraph printer circuits. It is expected that by the end of 1928 the system will be so extended that practically all of the cities in the state will be covered.

Several conflicting tendencies are noted in traffic signaling, particularly with respect to the colored lights or equivalent devices employed. While the green-amber-red cycle of signals has been adopted by many cities, others have favored either more or less complex arrangements. Centralized control of the street signals is being extended and while difficulties are experienced in so synchronizing operations as to minimize hazards and delays, it seems likely that this problem will ultimately be solved.

The blinker signals for outlying locations or crossings where there is little congestion are quite effective, particularly when equipped with Fresnel lenses. The gas type of blinker signal, using a tank of compressed gas for supplying the light jet has been superseded in many cases where electricity is available by a type using electric lamps.

H. W. DRAKE,
*Chairman.*

# Production and Application of Light

## ANNUAL REPORT OF THE COMMITTEE ON PRODUCTION AND APPLICATION OF LIGHT*

*To the Board of Directors:*

### INTRODUCTORY

The following report of the Committee on Production and Application of Light, as on former occasions, consists chiefly of a résumé of the more notable achievements of the year in the art of lighting by electricity. It has been compiled from information supplied by members of the committee and by other authorities in their respective fields who have kindly cooperated with the committee.†

## Production of Light

Most developments during the past year in the production of light have taken the form of refinements of design and adaptations of existing types of illuminants rather than of radically new methods or principles of light production.

### INCANDESCENT FILAMENT LAMPS

*Small Multiple Lamps.* Within the past year a new and smaller 10-watt tungsten filament lamp for 110-, 115-, or 120-volt service has been placed upon the market. This lamp has a bulb 1⅜ in. in diameter, designated "S-11" and a new base termed "intermediate," which is approximately ⅝ in. in diameter and ¾ in. long, standing in dimensions between the medium screw base and the candelabra base. This is a new size in the group of multiple lamps. It has been developed for places where physical limitations make the use of lamps of previously existing standard types difficult or impracticable. It is designed to yield an average life of 1500 hr. at a rated efficiency of 7.85 lumens per watt. It is available in coated bulbs in any of seven colors, the coatings being of a nature to withstand outdoor service. This lamp is expected to find wide use, especially in electric signs of the smaller sizes, in the design of which it has been difficult to achieve artistic effects with lamps of larger physical dimensions. Other uses to which the new lamp lends itself are outdoor decoration as of Christmas trees and illumination of small lighted ornaments which have recently appeared on the market for interior home decoration. It may also find application in the extension of cove lighting to residences where it has been extremely difficult to adapt this method of illumination due to the physical dimensions of the lamps heretofore available.

Another new lamp employing the intermediate base has recently been developed and placed upon the market in a bulb designated C9-¼. This lamp is rated at 10 watts, 115 volts and is designed to yield an average life of 600 hr. at a rated efficiency of 8.95 lumens per watt. It is intended primarily for lighting of Christmas trees and is available in coated bulbs in any of seven colors. Fig. 1 shows the two new intermediate base lamps in comparison with the 10-watt S14 medium screw base sign lamp.

In addition to these new lamps employing the intermediate base, the 15-watt flame shape bulb decorative lamp for 110-, 115-, and 120-volt service, formerly fitted with candelabra base is now available also with intermediate base.

A complete line of sockets and adapters for intermediate base lamps is now upon the market, as well as strings of seven sockets wired in multiple for Christmas tree and other decorative lighting.

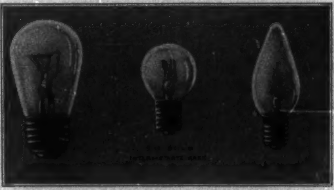

FIG. 1—10-WATT MULTIPLE LAMPS

*Very Large Lamps.* The successful production of incandescent lamps in sizes up to the 10-kw. lamp marks a distinct advance in the art of lamp manufacture and prepares the way for even larger sizes if they shall be needed. These extremely large lamps are manufactured for special purposes such as the lighting of aviation fields and motion picture studios. These applications are still in the developmental stage, though many installations are functioning satisfactorily.

*Projection Lamps.* A new development in the manufacture of incandescent lamps of the smaller sizes for projection purposes is the use of the "coiled-coil" filament by means of which the over-all dimensions of the light source are materially reduced, an object which is much sought in light projection. The resulting increase in uniformity and intensity of screen illumination has been a considerable factor in the growing popularity of home motion picture projection.

In certain types of concentrated filament lamps for light projection, more accurate and automatic positioning of the filament is attained through the use of a prefocused base consisting of a separate sleeve attached to an unthreaded base shell after the lamp has been otherwise finished.

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*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

The over-all dimensions of filaments of 750- and 1000-watt lamps for general service have been reduced in the interest of improved accuracy of light projection in flood lighting and of better distribution in the case of high-mounted industrial reflectors.

*Street Railway Lamps.* Two new lamps in inside frosted bulbs have been made available during the past year for street railway service. One of these is a 36-watt vacuum type coiled filament lamp designed for operation five in series on circuits of from 525 to 650 volts. The other is a low voltage, gas-filled lamp designed for operation at 30 volts per lamp, with approximately 20 lamps in series on the street railway circuit. This lamp has a special device incorporated in the lead-in wires by means of which the circuit is reestablished in case of the failure of the lamp filament. Being designed for low voltage operation, it has a relatively short and heavy filament and is therefore relatively sturdy; being of the gas-filled type and having a comparatively heavy filament, its light output per watt consumption is 40 to 50 per cent greater than that of the clear bulb, straight filament, vacuum type lamp designed for like service.

*New Large Bases.* In order to strengthen the attachment of the base to the bulb in the case of certain of the very large sizes of lamps, a Mogul screw base has been developed which, in addition to the cemented joint, has a mechanical clamp around the neck of the bulb.

For heavy current lamps taking more than 25 amperes and operating in the base down position, there has been standardized a two-prong base which is designed to overcome heating difficulties due to current density and contact resistance experienced with former types of bases.

*Short Circuiting Device.* To extinguish the arc which may be formed upon the failure of the filament in the smaller street series lamps and to maintain a closed series circuit, the lead-in wires have been brought into close proximity for a certain distance. If the arc travels along the lead wires the globules of metal on the ends of the two wires unite and short circuit the arc before it has an opportunity to damage the base of the lamp and the socket.

*Carbon Lamps.* Though the use of carbon filament lamps shows a decrease each year, the numbers of these lamps which are still in service and the numbers which are sold each year are very large. Carbon lamps seem to be particularly popular in colored bulbs and in bulbs of special decorative or novelty types. For purposes of illumination their use is, of course, uneconomical, but for decorative use they appear to meet a certain small demand.

*Operating Voltages.* The standardization of lighting circuit voltages continues to show progress from year to year. It is estimated by the lamp manufacturers that at the present time in this country 94 per cent of the population within reach of electric service is in territories served by some one standard voltage (110, 115, or 120) and that more than 99 per cent is within territories served by one or more than one standard voltage, leaving only a fraction of one per cent distributed among the odd voltages between 100 and 130. The voltage used most generally is 115. It is estimated that 59 per cent of the population within reach of electric service is provided with electricity at this voltage.

### SEARCHLIGHTS

The trend of development of military searchlight design since the war has been toward greater beam candlepower, lighter weight, greater mobility, and improved methods of control. There were two important developments in 1927.

One of these was the incorporation in the searchlight unit of a comparator system which makes it possible for the searchlight to be guided from a distance by accurate data transmitted electrically from a sound-locator station to the searchlight station. In anti-aircraft defense the pointing of the searchlight at the target is thus greatly facilitated.

The other development was the successful production of a 60-in. mobile searchlight unit employing a 250-ampere high intensity arc operated by a 25-kw. generating unit, and developing 1,385,000,000 maximum beam candlepower.

In order to facilitate signaling, searchlights of the smaller sizes in the Navy are being adapted to the employment of the incandescent lamp. Similar signaling searchlights using 1000-watt projection lamps have unique advantages in the submarine service in that the pressure on the projection drum may be equalized by allowing water to enter the unit.

### GASEOUS CONDUCTOR LAMPS

*Sign Types.* The neon tube lamp for display and sign service has grown in popularity during the last few years. By the use of various mixtures of gases and also by the employment of fluorescent glass tubing a number of color effects is obtainable, though some of these are not entirely stable at the lowest temperatures attained in the northern part of the United States. These signs require for operation a relatively high voltage and are characterized by a low power factor (usually below 50 per cent) when supplied with alternating current. On the other hand the efficiency of light production of the orange-red neon tube sign is relatively high and the guaranteed service life is long.

The vivid color contrast with daylight offered by neon tube signs tends to promote their use in daytime as well as at night.

*Hot Cathode Lamps.* The hot cathode neon lamp, a very recent development in this field, consists of a glass tube similar in form to that of the mercury vapor lamp now in general use, but filled with neon gas. The discharge through the gas is started and facilitated by the heating of the cathode. By this means the voltage drop at the electrode is reduced from 250 to 30 volts, making possible the operation of the lamp directly on a 115-volt a-c. or d-c. circuit. In this lamp the absence of electrode disintegration permits the passage through the tube of a comparatively large current with a resultant high intrinsic brilliancy and candlepower. It has been tried with some success in the illumination of opal letter signs, in the marking of pier heads and aviation fields and, in the form of a close spiral mounted at the focus of a parabolic reflector, as an airway beacon. It may be noted that this new form of neon lamp may be used in combination with the mercury vapor lamp to produce with high efficiency, light which is apparently white in color and which is expected to find application in color and panchromatic photography.

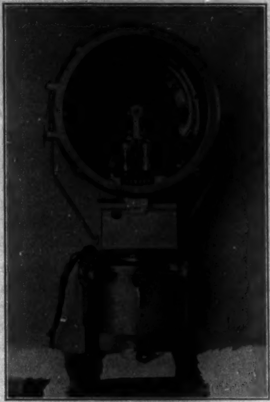

Fig. 2—Neon Induction Beacon

*Negative Glow Lamps.* The negative glow socket type neon lamp (known as the G10 indicator lamp) which was mentioned in the 1926 report of this committee has undergone further development during the past year. The present form of this lamp is designed for operation on 115-volt a-c. circuits. It consumes about one-third of a watt and emits somewhat less than one-tenth of a candlepower. Its field of use is primarily that of an indicator or night lamp. The corresponding lamp for d-c. service is under development but is not yet available.

*Television Lamp.* A prominent position in the recent successful demonstrations of television has been occupied by a neon lamp of a type specially designed for that class of service. The neon lamp is uniquely adapted to that purpose by virtue of its instantaneous response to variations of voltage.

*Induction Lamp.* The electrodeless discharge in neon, in the form of the induction lamp has recently been employed experimentally as a light source for airway beacons. The bulb enclosing the luminous gas is of clear fused quartz about 1½ in. in diameter and is mounted at the focus of a searchlight reflector. A short wave pliotron oscillator mounted in the reflector housing generates the high frequency current necessary to excite the gas within the bulb. Due to its orange-red color the neon induction beacon illustrated in Fig. 2 is said to excel in visibility at a distance in both clear and foggy weather when compared with other sources of equal beam candle-power.

## APPLICATION OF LIGHT

## Interior Illumination

### INDUSTRIAL LIGHTING

The year has witnessed advances both as to the general standards of industrial lighting and the extent to which modern methods are employed.

The industrial activities referred to in last year's report have undoubtedly secured a wider recognition of the value of good illumination in promoting workers' welfare and safety as well as speedy and economical production.

A survey of a considerable number of industrial plants on the lines of one of the largest electric service companies showed that on the average the electrical energy consumed for lighting approximately equaled that used for power purposes. Since this lighting service company has been particularly active for over a decade in promoting industrial lighting, the lighting of these plants is presumably better than would be found in most cities. But even allowing for this, the results indicate a more intensive use of light than would generally have been expected.

The Department of Labor and Industry, State of Pennsylvania, has adopted regulations for emergency lighting of places of public assembly and places where persons work after darkness. The rules call for an emergency illumination of at least half a foot-candle on the floor at exit doors, hallways, etc., leading to outside building exits, and of at least a quarter foot-candle on the floors of auditoriums. Control of the supply must function without dependence upon manual operation. The source of energy must be separate from that of the main lighting system, and when secured from outside the building must be supplied by two generating stations, an approved automatic throw-over switch being required.

### COMMERCIAL LIGHTING

Though the past year has been marked by no outstanding development in commercial lighting practise, it has seen a more widespread application of illumination due to a better appreciation of its utilitarian and advertising value. While the present practise in the majority of stores and offices is to provide general illumination with diffusing glass enclosing globes, there is a growing demand for lighting equipment of the semi-indirect type. In the main corridors of the newest office buildings and in hotel lobbies unique luminaires designed along the lines of modernistic art have appeared. These innovations in design not only provide an interesting variation but it is thought that they may lead to radical changes in types of commercial lighting equipment.

In the lighting of window displays the tendency has been to advance to higher intensities as the level of street illumination has risen and as the number and brilliance of electric signs have increased. The use of colored lighting and the employment of spotlights to create striking contrasts have been practised extensively during the past few years.

The more general use of color matching units is notable. Unfortunately such applications are peculiarly liable to misunderstanding and misrepresentation, both of which have been present to no small degree. Practise in artificial daylighting is in need of clarification.

## RESIDENCE LIGHTING

*The Modernistic Trend in Lighting Equipment.* For several years European artists and designers, notably the French, have been striving to develop a style which will express twentieth century tendencies. Their work has influenced furnishings of all kinds, including lighting fixtures. These modernistic fixtures usually employ plane rather than curved surfaces and strong, pronounced lines. Color is used to advantage and there is remarkable absence of unnecessary applied decorative bits. Almost without exception exposed bare lamps find no place in this equipment. The lamps are generally hidden from view, the light being diffused by some external medium.

The modernistic movement is beginning to find its way into American homes and it is to be anticipated that it will have considerable effect on home lighting practise. Already a number of progressive American manufacturers is showing some excellent fixtures in this new spirit. Two wall units and a unique table lamp of domestic manufacture are illustrated in Fig. 3.

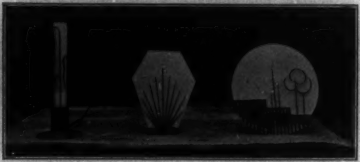

Fig. 3—Luminaires in the Modernistic Spirit

*Use of Light for Ornament.* Mention was made in last year's report of the development abroad of artistically lighted pieces of decoration. These lighted ornaments in general furnish no useful illumination, but give touches of high light in color about a room. They have been very aptly termed "the jewelry of the lighting installation." In the past year a great number of these devices has been imported and sold by the leading shops here. The tremendous potential field in America, however, cannot be covered by importations, and one of the leading American manufacturers has placed on the market a line of such ornaments, several of which are shown in Fig. 4.

Fig. 4—Lighted Ornaments for Household Decoration

*Residence Wiring.* The increasing cost of residence wiring and the growing tendency toward unreasonable restrictions in the use of materials and methods are believed in certain quarters to be serious hindrances to the development of the residential use of electricity. As a result of this feeling study has been devoted during the last few years to the problem of surmounting these obstacles in the way of household electrical development.

It is believed that there are three important factors underlying the undesirable conditions mentioned. These factors are, first, lack of adequate skill in planning the average residence wiring system; second, lack of economical wiring materials; and third, the tendency to employ the electric wiring codes as obstructions to new development and progress.

The first condition is being corrected in many localities through the employment by the central station companies of home lighting experts and by the propagation of the so-called "Red Seal" plan. Looking forward to the amelioration of the other two unfavorable influences there is considerable agitation for the development of lighter and less expensive wiring materials, and for the modification of the electrical codes if necessary to permit the use of such materials.

## THEATRICAL LIGHTING

The growing importance of stage lighting in dramatic production has led to the institution of a course in stage lighting in the Department of Drama at Yale University. This is perhaps the first serious attempt to teach lighting as a part of dramatic production. The course, which is open to students of some experience, involves a comprehensive study of the science of lighting particularly from the standpoint of history, physics, psychology, electricity, illumination, instruments, and control. This is followed by the study of the use of light on the stage and by practise on regular productions.

*Motion Picture Lighting.* The almost universal use of panchromatic film and the closer attention to operating efficiencies and economies are two principal factors which have brought about in some studios the substitution of incandescent lamps for other illuminants. It has been found that the spectral quality of the light from incandescent lamps is well suited to panchromatic film and by their use better color rendition is obtained than with other illuminants. It is stated that by the use of incandescent lighting the labor and power costs for lighting are considerably reduced and, further, that it is found to be more flexible, more easily controlled, and more pleasing to those working under it than are other systems. Producers of the so-called talking pictures have found incandescent lighting desirable in order that the noises of arc lamps may not be recorded.

The usual lighting requirements for motion picture production call for a general illumination of from 200 to 500 foot-candles over the entire area to be photographed and, in addition, concentrated beams of from two to five times these values for modeling the principal actors or for bringing out certain parts in contrast with the rest of the set. The larger sizes of incandescent lamps up to those of 10-kw. rating are used.

One of the recent developments in equipment for amateur motion photography is a portable reflector containing a standard 500-watt, T20 bulb, 100-volt projection lamp to be operated on the usual 115-volt house lighting circuit. This over-voltage operation, while reducing the average life of the lamp from the normal figure of 50 hr. to about 5 hr., greatly increases the amount of light produced as well as its actinic value and renders possible the use indoors of amateur motion picture cameras which have heretofore been dependent upon outdoor illumination.

During 1927 there has been developed and placed on the market a new type of motion picture projector which utilizes a 60-ampere high intensity arc with an ellipsoidal reflector as optical condenser equipment. With this new type of projector it has been possible to obtain screen brilliancies equivalent to those previously obtained with a 120-ampere high intensity arc and the usual condenser lens system.

## Exterior Illumination

### STREET LIGHTING

A tendency which has recently become evident in street lighting practise is the supply of 20-ampere series lamps from 20-ampere series circuits instead of through the medium of individual transformers from circuits carrying small currents. Besides the elimination of the individual transformers, this practise results also in the loading of the series conductor more nearly to its capacity and in the reduction of the voltage for which it must be insulated.

A method of remote control for street lighting circuits employing high frequency carrier-current impulses transmitted along the same conductors as the power current has been developed. The principal advantage of this method of remote control is that the power conductors are utilized for the transmission of control impulses without interference with their own function and without need for additional control conductors. It possesses a high degree of flexibility and is not subject to limitation of distance between transmitter and receiver to the same extent as is a pilot-wire control system. The first practical installation of the carrier-current control system was made in Schenectady, N. Y. Later installations have been made in Bayonne, N. J., Rochester, N. Y., San Francisco, Calif., and Boston, Mass.

### RELATION BETWEEN STREET LIGHTING AND MOTOR VEHICLE HEADLIGHTING

Obviously there is a close relation between street lighting and motor vehicle headlighting. The practise in either field affects that in the other field.

If adequate street and highway lighting were everywhere available, there would be no necessity for powerful headlight beams. Since it is not likely to be economically practicable to illuminate all roads over which motor vehicles travel, there is no likelihood at present of eliminating such equipment.

On the other hand, as adequate lighting of streets and highways becomes more extensive, the practicability and desirability of driving for a considerable part of the time with dimmed or deflected headlighting is becoming more and more possible of realization.

Powerful headlights, such as are necessary to illuminate a highway, are subject to serious limitations. The known methods of eliminating glare from the eyes of other users of the highways are only partially effective and are not universally applied. Such glare is a source of discomfort and hazard. On densely traveled highways, the continual subjection of a driver's eyes to one headlight after another becomes quite serious.

Engineers who have given the most thorough study to the problem have reached the conclusion that its solution lies in the fixed lighting of highways carrying heavy traffic, and assert that suitable lighting is available and economically practicable in many such situations.

While the glare from automobile headlights is less serious in well lighted streets and highways, it is still objectionable, and since the use of powerful beams is unnecessary under these conditions, it is desirable to encourage the practise of avoiding their use.

The Committee on Street Lighting of the Illuminating Engineering Society has sought the cooperation of the Committee on Motor Vehicle Lighting of the same society in the consideration of this question. As a result of the joint deliberations, the following resolution has been accepted as representing the views of both committees:

"JOINT RESOLUTION ADOPTED MARCH 7, 1928, BY ILLUMINATING ENGINEERING SOCIETY COMMITTEES ON STREET LIGHTING AND MOTOR VEHICLE LIGHTING

"RESOLVED, that in the opinion of the Illuminating Engineering Society Committee on Street Lighting and of the Illuminating Engineering Society Committee on Motor Vehicle Lighting, powerful headlights on automobiles as used in open road driving are unnecessary and undesirable upon adequately lighted streets. Upon such adequately lighted streets the practise of dimming or depressing headlight beams is desirable and should be encouraged.

"It is further the opinion of these committees that it is practicable at this time to provide such adequate street light for traffic thoroughfares of American cities. In general, street lighting on such thoroughfares is believed to be adequate for this purpose when the street area between curb lines is illuminated to an average horizontal intensity of one-quarter foot-candle or more. This illumination can be obtained even under unfavorable conditions by an expenditure of about 100 lumens per linear foot of street. Where light is applied most effectively, and other conditions are favorable, a materially smaller value of generated lumens will produce adequate illumination and will suffice for driving with dimmed or depressed headlight beams."

## AUTOMOBILE HEADLIGHTING

The developments in automobile headlighting during the past year were characterized by structural improvements in headlamps and accessories and in the more extended use of the depressible beam system with two-filament lamps.

Among the difficulties encountered in attempting good headlighting has been the fact that headlamp construction often has been so poor that permanency of adjustment could not be expected. Also, headlamp mountings have been, in many cases, so badly designed and made that close adjustments have been difficult to obtain and when once obtained have been insecure. With respect to these matters there has been a material betterment. Furthermore, the incandescent lamps used are being made to closer factory standards, particularly with respect to positioning of the filament, (axial alinement and light center length), so that the day seems to be approaching when focusing adjustments on headlamps can safely be abolished. This will bring a great relief to the motorist and better average headlighting conditions on the road.

The belief has taken strong hold that headlight beams with a wide lateral spread below the horizontal are advantageous in night driving and the tendency is to use front glasses on headlamps which will give these wide spreads. This has brought up the difficulty that if the total available flux of light from a 21 cp. incandescent lamp is spread over as great an area as it seems to be desirable to illuminate, the beam intensities fall below a desirable limit, so that seeing is impaired. The use of the 21 cp. lamp is very extensive. In many states the use of higher candlepowers is prohibited. From a technical standpoint, however, it appears that proper illumination over the wide area which should be illuminated involves the use of higher candlepower lamps. Both the Lighting Division of the Society of Automotive Engineers Standards Committee and the Motor Vehicle Lighting Committee of the Illuminating Engineering Society, the former in connection with the preparation of the specifications for dual-beam equipment mentioned below and the latter in its last report have recognized this condition and have pointed out that the logical solution of future design involves a raising of the limit to 32 cp., a change which does not involve overloading the electrical equipment of the car.

The same committee of the I. E. S. during the past year has produced a draft of specifications for laboratory tests of optical characteristics of electrical headlamps intended to cover the so-called dual beam equipment for motor vehicles, and eventually to supersede the former headlight test specifications of the I. E. S. for the test of the single beam equipment. The Society of Automotive Engineers has cooperated in this matter and has adopted these specifications as part of its code of recommended practise. It is hoped that after a suitable trial period these specifications, with or without slight modifications, will be suitable for proposal to a sectional committee organized under the American Engineering Standards Committee procedure for adoption as an American standard.

The dual beam headlighting system discussed at some length in last year's report has been approved by all states as legal and has met with wide popularity. A large proportion of the new cars is now being provided with this equipment. By its use two things are accomplished: first, a great amelioration of the glare difficulty is obtained by the use of the depressed beam, and second, since the driving beam can be removed from the eyes of passing drivers, the adjustment of the headlamps may be such that the top of the beam is of higher candlepower than with the fixed beam equipment, thus providing a better driving light where the absence of oncoming cars renders it practicable to keep the beam in its normal position.

A promising research project directed toward the determination of the most satisfactory methods of automobile headlighting is being carried out at the Bureau of Standards under the technical direction of the Research Committee of the Society of Automotive Engineers with funds provided by the National Automobile Chamber of Commerce. The object of this investigation is to carry further by means of road tests, supplemented by laboratory work, experiments to ascertain the headlighting requirements of the driver under various conditions and how best to fulfil these requirements under definite conditions. The first part of this research, designed to show the effect on visibility distance of various road conditions and lighting distributions, has been completed. Progress is being made on the second part in which the effect of approaching lights will be considered as an additional factor.

### Signal Lighting for Traffic Control

On November 15, 1927, under American Engineering Standards Committee procedure there was approved as an American Standard a Code of Colors and Forms for Traffic Signals for Highways and Vehicles. This code includes lights used upon vehicles and also luminous signals used for traffic control, but it does not include non-luminous signs. The code establishes the use of green for GO, red for STOP, and yellow for CAUTION, and gives a scientific specification for these three colors. The code includes the type of signal to be used at railroad grade crossings to indicate the approach of a train.

The subject of non-luminous traffic signs is to be covered in a report of a committee of the American Engineering Council on Street Signs, Signals, and Pavement Markings. This A. E. C. Committee has been at work for more than a year and has nearly completed its report, which includes the choice of colors, forms, wordings, mounting positions, mounting heights, and various other details of street traffic signs as well as recommended practises for pavement markings. It is attempting to standardize the control of right and left turning movements where luminous signals are used in the hope of achieving some uniformity in the use of such signals. It favors the use of red and green only rather than red, yellow, and green; but where yellow is to be used it is hoped that it may be used in a uniform manner in all communities. Its report is now in the hands of a sectional committee of the A. E. S. C.

The A. E. S. C. code already approved provides that automobile headlights shall be white, yellow, or some intermediate hue. Tail lights are to be red and rear signaling devices are to be yellow. Other red and green lights are not to be displayed on either the front or the rear of vehicles. Conformance to this code will require the abandonment of red and green lights for route markers and for rear signaling devices.

In line with the standardization of the use of colored lights, the American Engineering Standards Committee has already approved of green as the standard color for exit lights from theaters and similar buildings.

### Sign Lighting

The National Electric Light Association, in the spring of 1928, sponsored two schools of electrical advertising which were held at the respective lighting institutes of the Edison and National Lamp Works of the General Electric Company. In addition to the technical aspects of electrical advertising, the schools stressed the necessity for cooperation between the various branches of the industry for the purpose of improving the value of this advertising medium.

The projection of advertisements upon low clouds in the sky has been made possible by the development of a huge lantern slide projector illustrated in Fig. 5. The application of this method has not as yet proved generally practicable, being decidedly limited by meteorological conditions.

The animated bulletin board type of sign consisting of figures painted with saturated colors and illuminated alternately by light of different hues continues to grow in popularity in spite of its limited color range.

Porcelain enameled steel letters are being used more extensively than in former years, particularly in connection with large roof signs. Their ability to withstand exposure to the weather and the ease with which they may be cleaned are important advantages over painted letters. The recent use of chromium-plated channel letters and borders in electric signs is one of the latest recorded developments in the sign art. The effect is apparently to multiply the number of lamps in the sign in consequence of the specular reflections from the polished surfaces. The non-corrodible quality of chromium plate renders it especially suitable for this service.

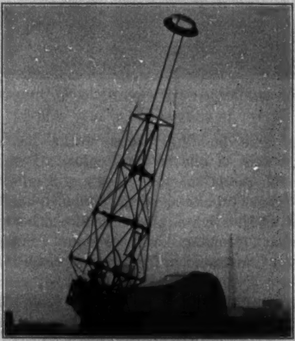
Fig. 5—Sky Projector

The increasing popularity of the neon tube is one of the notable developments in this art. It has been stated to the committee by one of the leading manufacturers that during the last four years about 700 neon electric signs have been installed in the New York metropolitan area and that more than 4500 such signs have been installed throughout the United States.

### Lighting of Building Exteriors

The floodlighting of office and public buildings has advanced rapidly during the last few years. Architects have manifested greater interest in lighting as a means of bringing out pleasing features of design and in consequence many buildings at present under construction are provided with ample wiring at the proper places for floodlighting. In the case of tall buildings the trend of practise is to light the upper stories which are visible from the greater distances and for the lighting of which facilities are afforded by the modern setback style of construction. During the past year there has been a distinct tendency toward the employment of color in floodlighting. The instances of the use of color range from small installations with touches of color here and there to large buildings whose entire facades are bathed in light of one or more colors. Perhaps the most notable recent example of colored floodlighting is the new 23-story building of the Philadelphia Electric Company which is lighted above the fifteenth story with continuously changing tints of four colors. This installation (illustrated in Fig. 6) comprises a total of 467 projectors consuming 262 kw., which is equivalent to about 9 watts per sq. ft. of lighted area. The colored lamps, which are connected directly across the line, are supplemented by clear white lamps connected in series with motor-driven dimmers. By this means the colors are diluted with white light in continuously changing proportions. The colored lamps comprise about two-thirds of the total wattage and the clear lamps one-third.

Fig. 6—Floodlighting of Edison Building, Philadelphia, Pa.

Fig. 7—Floodlighting from Ornamental Street Lighting Posts

The supply of floodlighting projectors from series street lighting circuits is an interesting development of the recent past. In this class of installation the floodlights burn on the same schedule as the street lamps, and are owned, installed, and maintained by the electric service company.

Another interesting method (illustrated in Fig. 7) of floodlighting buildings not exceeding 100 ft. in height, is the installation of projectors in the ornamental tops of street lighting posts located along the curb. In addition to the projection lamp in this type of installation an auxiliary lamp of about 200-watts rating is required in each post top in order to raise its brightness to a point where its appearance bears out its function as a light source. This type of installation has the merit of a pleasing appearance in the daytime as well as at night and is particularly well adapted to those cases where no out-of-sight location can be found for the projectors.

### Lighting of Railroad Yards

Floodlighting is becoming recognized as the standard method for the artificial illumination of railroad yards and its application is, therefore, rapidly extending. The need for more exact engineering data and method in designing floodlighting installations and selecting lighting units has been recognized. The Committee on Illumination of the Association of Railway Electrical Engineers has continued its active study of this subject, and, with the assistance of a subcommittee comprising specialists in photometric and illuminating engineering work, has prepared a "General Procedure for Photometry of Incandescent Floodlights" which it has recommended for adoption as standard practise for testing and rating floodlighting projectors.

### Railroad Signaling

During 1927 automatic signals were installed upon 5127 mi. of railroad. This record has not been equaled in any previous year. The preference for light signals is indicated by the fact that of the total number of signals installed during 1927, 74 per cent were light signals and 26 per cent were semaphore. The proportion of light signals tends to increase from year to year. Of the light signals installed during 1927, 82 per cent were colored lights, 16.8 per cent were position lights, and 1.2 per cent were color position lights. One of the outstanding developments of 1927 was the placing in service of a centralized dispatching system on the Ohio division of the New York Central Railroad. This installation represents the accomplishment of the idea of operating trains by signal indication without written train orders or operators at intermediate stations. All signals and passing side switches are power-operated and under the control of the dispatcher at a central point.

### Lighthouses

Since the first practical application of the incandescent electric lamp to large lighthouses at Cape Henry

Light in 1922, practically all of the coastal lighthouses of large size in this country have been so equipped wherever central station service is available or where a local generating plant can be maintained. During the past year ten light stations and three lightships were equipped with electricity. Small electric lights, the current for which is supplied by a battery of primary cells, are to some extent being substituted for oil burning post lights on inland rivers and similar locations. These outfits have been designed to operate without attendance for several months.

A relatively recent development in the application of electricity to the lighthouse service is the automatic lamp changing device, actuated by a no-voltage relay, which swings into focus and lights a spare lamp in the event that the first lamp burns out in operation. Though commercial types of incandescent electric lamps have been found satisfactory in lighthouse lenses of the smaller sizes, and though they produce adequate beam intensity in lenses of any size, they are not well adapted for use in large lenses designed for other illuminants because the filament is not large enough to provide sufficient vertical divergence of the beam in fixed lenses, and in revolving lenses the length of flash provided is of too short duration. Considerable experimentation along the lines of variations of filament shape and frosting of bulbs has resulted in the development of several lamps for this service which represent a great improvement over the general service types.

### LIGHTING FOR AVIATION

During 1927 much work has been done in the lighting of airways in order to promote the safety of night flying. At the present time 5800 mi. of air route are provided with flying facilities which include beacon lights 10 mi. apart, or closer where required, lighted intermediate landing fields 30 mi. apart, radio communication service for weather information and forecast, reports of arrivals and departures, and direction and control of aircraft in flight.

The beacon lights are erected on 50- or 75-ft. steel towers at the bases of which are chrome yellow arrows 56-ft. long to indicate the line of flight. The number of the beacon is painted in black on the arrow for daytime identification. The beacon light consists of three units, a revolving searchlight synchronized with two flashing red course lights. The revolving beacon has a 24-in. parabolic mirror and a 1000-watt, 110-volt T20 incandescent lamp designed to yield an average life of 500 hr. The beacon develops a beam intensity of between two and three million cp. Its axis is elevated two deg. above the horizontal and it is rotated about a vertical shaft by a motor and worm gearing at a rate of six rev. per min. Auxiliary contactors on the vertical shaft interrupt the current to the course lights according to a code by which the pilot identifies the beacon.

Each course light consists of a 500-watt, G40 incandescent lamp in a 14-in. parabolic reflector with a red or amber 30-deg. spreadlight cover glass. The electric circuits are controlled by astronomical clocks which turn the lights on at sunset and off at sunrise. Where commercial electric service is not available two-kw. full automatic gasoline engine generators are installed in duplicate. In the event of engine failure a relay places the stand-by generating unit in operation.

Intermediate landing fields are marked with a revolving beacon, a boundary lighting system, obstruction lights, and an internally lighted wind cone. The fields usually have two landing strips at right angles to each other, each about 500 ft. wide and 2000 ft. long. The boundaries of the landing strips are marked by 15-watt or larger multiple lamps in clear white refractor globes spaced about 300 ft. apart or by series lamps of equivalent candlepower. Green range lights mark the favorable approaches and 25-watt or larger multiple lamps in red globes are mounted on all neighboring obstructions.

To meet the requirements for terminal fields 425 airports have been established or are under construction by municipalities in the United States. The Department of Commerce has established an airport section to cooperate with city officials for proper selection and development of airports. Extensive tests were made during the past year in the landing of aircraft at night under varying conditions and floodlighting systems.

The outstanding developments in airport lighting during the year were a new system of grouping of incandescent floodlight units on one or more sides of the landing field, an intermediate size dioptric floodlight unit using the 5-kw. incandescent lamp, illuminated field markers and wind-direction gages and a 55-ampere high intensity arc floodlight unit with 2 deg. vertical and various degrees of horizontal spread of beam. Neon tube beacons and boundary lights have been advanced in development during the year and it is understood that in Great Britain and Germany they are employed very generally in lighting for aviation. A practical method has been demonstrated for automatically controlling landing field floodlights through switches actuated by the noise of the airplane or by a whistle of distinctive tone mounted on the plane.

### LIGHTING FOR NIGHT RECREATION

Artificial lighting is being used more and more to extend the uses of recreational areas into the dark hours. Lighting installations for night tennis, football, races, bowling on the green, hockey, horseshoe pitching (quoits), and indoor baseball are numerous and assure the practicability of night sports. Fig. 8 shows a court illuminated for playing quoits after dark. Extensive investigations at Lynn, Mass., indicate that in no very distant future the great national game of baseball may be played at night under artificial illumination.

During the past year special progress has been made in the application of artificial light to swimming pools.

In addition to levels of illumination of the order of 5 to 10 foot-candles over the entire pool area to insure safety and comfort it has been found desirable and feasible to provide, in the deeper parts, under-water illumination from units below the surface. Equipment which can be installed quite economically has recently been made available for this service.

*Christmas Lighting.* More attention has been paid to decorative Christmas lighting this year than ever before. Over fifty communities conducted contests during the holiday season in the decorative lighting of residences, all of which were successful in greater or lesser degree. Greatest interest, as manifested by the largest number of entries, has come where the contest has been divided into several classes or districts so that moderate homes were not expected to compete on an equal basis with wealthy homes. In Fig. 9 is illustrated an example of the result achieved by effort applied in this direction.

FIG. 8—ILLUMINATED COURT FOR QUOIT MATCHES

### UNDERWATER LIGHTING AND DIVING LAMPS

The standard diving lamp adopted by the U. S. Navy and approved by marine salvage companies now consists of a 1000-watt G40 extra heavy glass bulb lamp, 115-volt range, with concentrated filament construction. These lamp bulbs are tested to withstand a pressure of 150 lb. per sq. in., which suffices for submersion to a depth of 300 ft. The bulb is mounted in a housing some 18 in. long with a non-tarnishing metal reflector 11 in. in diameter. In operation the lamp bulb is in direct contact with the water, being protected only by a heavy wire screen across the mouth of the reflector. The problem of overcoming water leakage has been solved by the use of a special insulating sleeve surrounding the base of these lamp bulbs. To prevent the crushing of the lamp base and the seal, which are the weakest points of the structure, special reinforcement has been introduced. These lamps have proved very useful in recent salvage operations on the submarine S-4. Although the water near the bottom was very muddy, the divers there engaged reported good visibility at distances from 3 to 6 ft. Experiments have been conducted to ascertain whether colored light would be more effective than white light in promoting visibility under water, but the results have been chiefly of a negative character.

During the past summer underwater lamps were used in a study of tropical marine life off the coast of Haiti. Both clear and colored lamps were used and the attracting power of light for certain fish seemed well demonstrated. It is reported that electric incandescent lamps are in use as bait by Japanese fishermen.

### LIGHTING FOR AGRICULTURE

Recent investigations into the relation of light to plant growth and maturity have followed three paths, first, the relative effects of radiations of different wavelengths, second and third, the effects of variations in the relative and absolute lengths of the alternate periods of light and darkness. Different varieties of plants do not seem to react in the same way to the same conditions of irradiation. It has been reported that the growth of some plants has been stimulated and the content of certain valuable ingredients increased by exposure to the ultraviolet end of the spectrum of sunlight. Other investigators have concluded that, in general, the ultraviolet portion of the spectrum of sunlight has no great effect on plant growth, time and amount of flowering, or the weight of tissue produced. It has been observed that certain pigments, as the red in mignonette lettuce and the purple in purple cabbage, are intensified by violet and ultraviolet radiation. It has been shown by several experimenters in this field that ultraviolet radiation of wave lengths shorter than 248 millimicrons is very injurious to growing plants.

FIG. 9—DECORATIVE LIGHTING OF HOUSE FOR HOLIDAYS

Previous investigations have shown that long periods of illumination produce in some plants increased vegetative growth while in other plants they bring about early maturity. Recent experiments with the variation of the absolute lengths of the alternate periods of light and darkness (their relative lengths remaining constant) have led to the conclusion that with plants in which flowering is favored by short days, as well as with those in which the opposite is true, the general effect of relatively short alternations of light and darkness on reproductive activities is much the same as that produced by long days or continuous illumination. However, it was also observed that the short light-darkness alternations may bring about more or less serious nutritional disturbances. As the periods are shortened the plant seems to be weakened until a point is reached at which the growth begins again to improve. This point in one case was equal periods of 15 sec. of light and darkness. In another case it was found that periods of 0.004 sec. duration produced the same rate of assimilation in the plant as did continuous illumination.

The attraction of light for insects has been used for many years in luring them to their destruction. A recent application of this principle was made in Alabama where fruit worms had caused severe losses in the tomato crop. With 100- and 200-watt lamps and flat reflectors suspended 5 ft. from the ground and over pans of water covered with kerosene, the protection was reported to be so complete that only 35 worm-infested tomatoes were found in two acres, whereas neighboring unprotected fields suffered losses from 30 to 50 per cent.

That color is a factor in the attraction has been shown in some results obtained at the State Experiment Station at Geneva, N. Y. It was found that "tent caterpillars," a most ravenous insect pest, would leave young apple twigs and gather in places where there was plenty of light though little fodder. With differently colored lights, the apparently hungry caterpillars usually went directly to those of a pale yellow. Some preferred a deeper yellow, but red light appealed to only a few.

From other quarters information has been received that while many experiments, some of them very careful tests, have been made with lights in the control of different insect pests such as the cotton worm, cotton boll weevil, codling moth, Japanese beetle, etc., the results have not been sufficiently favorable to indicate that any material help may be expected from the use of light traps under the conditions of experimentation. It is believed that there is room for considerable further experimentation in this field, as with lights of different colors and different intensities.

The use of artificial light in poultry houses during the winter months has become a common practise on many poultry farms. The usual method is to turn on the lights for a short period morning and night in order to extend the period of daylight, thus stimulating the activity of the hens and increasing their food consumption and egg production. In addition to the use of artificial light in this connection, electricity is being used in experimental work to furnish ultraviolet rays to young chicks and also to laying hens which are kept confined where they do not get direct sunlight, the effect of the ultraviolet radiation being to promote bone formation and to prevent the occurrence of leg weakness, a condition resembling the disease in human beings known as rickets. The more common practise, however, is to accomplish this result by administering with the chickens' feed a ration of cod liver oil which has the same specific effect as ultraviolet radiation.

## Other Topics

### SOURCES AND APPLICATIONS OF ULTRAVIOLET RADIATION

The general interest in the health promoting use of ultraviolet radiation has stressed the need, on the one hand, for windows transmitting all of the sun's short wave radiation, and on the other hand, for artificial sources emitting little or no radiation of higher frequency than that present in direct sunlight. The former need has been met by a variety of more or less satisfactory materials for use in place of ordinary window glass. Of these materials the degree of transparency to ultraviolet radiation varies greatly. Moreover, the transparency of certain materials tends to deteriorate with exposure.

The latter need arises from the hazard incidental to the use by laymen of the high intensity, high frequency ultraviolet sources formerly used only by the medical profession, and also from a recent tendency to attribute the maximum therapeutic value to those wave lengths in the immediate neighborhood of 300 millimicrons. This need has been met by the use of the new window glasses as filters in connection with arc lamps which have long been used as artificial sources of ultraviolet radiation. However, much attention has been given to the problem of developing a new source characterized by a maximum possible emission in the region from 280 to 320 millimicrons, with no emission of shorter wavelength and a minimum of radiation of longer wave length. It is expected that such a source of ultraviolet radiation will appear on the market within the next year.

The types of artificial sources at present available are being widely sold for use not only by physicians but for home use under medical supervision. Artificial "solariums" are being generally established in connection with athletic clubs, Y. M. C. A.'s, Y. W. C. A.'s, and sanitariums throughout the country. Baby clinics primarily for ultraviolet treatment and prevention of rickets are in operation in many large cities.

Two new industrial applications have been well established during the past year. The application of ultraviolet radiation from artificial sources to the hardening of the varnished surface of patent leather has been successful in effecting a higher quality of product with a much shorter treatment than was possible by the former method of exposure to sunlight. The exposure of dried milk powder to ultraviolet radiation has resulted in the production of an infant food having marked antirachitic properties. A similar use of ultraviolet radiation in connection with the preparation of other food materials is under investigation.

### PHOTOMETRY

Recent progress in photometry has taken the form of refinement of existing methods and instruments and of increased knowledge of the characteristics of the photoelectric cell. The advent of the four element vacuum tube has made it possible greatly to improve the sensitivity, speed, and precision of photoelectric spectrophotometry. The photoelectric cell containing a monomolecular layer of caesium which has recently become available, represents a distinct advance over the earlier types in stability of color sensitivity and in approach to eye sensitivity.

A recent development in the photometry of floodlights and other projectors has been the use of a concave spherical mirror in place of a diffusing hemisphere for integrating the light flux over a unit of solid angle.

The standard method for photometry of floodlighting projectors, mentioned elsewhere in this report, which has been formulated by the Committee on Illumination of the Association of Railway Electrical Engineers, is intended to render possible the comparison of results of photometric tests made on projectors by different laboratories. This is achieved by standardization of testing conditions and methods of computation of results from test data. Briefly, the method provides that the light flux within a solid angle of one square degree be measured in an integrating device at a distance of not less than 100 ft. Observations are taken at approximately 100 stations uniformly spaced throughout the beam, and in addition, at a series of stations on eight equally spaced lines radiating from the axis of the beam and extending to the limits of the lighted area. This method of integrating the light output over a solid angle of one square degree minimizes erratic results due to traces of filament image in the beam. Since the beam limits are defined in terms of the maximum candlepower value, individual test results of single projectors show some variation in beam efficiency. Further refinement of the method is under consideration with a view to reduction of these variations.

The great differences in the intensities and the spectral characteristics of the ultraviolet radiations from the various sources make it desirable to be able conveniently to compare the radiations from several sources in terms preferably of some standard unit of intensity. Unfortunately no convenient method of accomplishing this has been standardized, though it has been suggested that the intensity of the ultraviolet component of sunlight at least may be inferred from photometric measurements, the factor of proportionality having been determined for the given locality by radiometric measurements in the laboratory.

### MISCELLANEOUS APPLICATIONS OF LIGHT

An interesting and novel application of light is in a device recently developed for measuring the change in length of a small specimen of magnetic material upon magnetization. This change of length is of the order of a billionth of an inch. In this apparatus the image of an illuminated portion of a ruled grating is reflected back upon another portion of the grating by a pivoted concave mirror which is arranged to tilt slightly when the length of the specimen changes. Behind the second portion of the grating is a photoelectric cell. As the mirror tilts the image moves across the grating, causing a variation in the amount of light transmitted to the photoelectric cell. The response of the cell, as indicated by a sensitive galvanometer, is a measure of the tilt of the mirror and of the change of length of the specimen.

A recent application of ultraviolet radiation and the photoelectric cell is in a device for the automatic concentration of ores. The crushed raw ore on a belt passes under a source of ultraviolet radiation which causes the pieces of valuable material to fluoresce strongly, while the pieces of worthless rock remain unaffected. A photoelectric cell screened from the ultraviolet radiation picks up the visible light of the fluorescent material and actuates a device which separates this material from the rock.

### INTERNATIONAL CONSIDERATION OF ILLUMINATION TOPICS

The occasion of a plenary meeting of the International Commission on Illumination in America will be marked by an International Illumination Congress during the week of September 24, 1928. In addition to reports of technical committees of the I. C. I., there will be papers and discussions on a variety of lighting topics. This meeting is expected to bring together leading lighting experts from the several countries and bids fair to advance understanding through the exchange of technical information with results beneficial to all participating countries.

PRESTON S. MILLAR, *Chairman.*

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| C. B. Veal, | Research Manager, Society of Automotive Engineers, Inc. |

# Electrochemistry and Electrometallurgy

## ANNUAL REPORT OF COMMITTEE ON ELECTROCHEMISTRY AND ELECTROMETALLURGY*

*To the Board of Directors:*

The Committee on Electrochemistry and Electrometallurgy makes its annual report as follows:

The revision of the Institute's standards for storage batteries which was proposed by this committee several years ago has been completed by Working Committee No. 37. The revised standards were adopted by the Board of Directors February 16, 1928 and have been published.

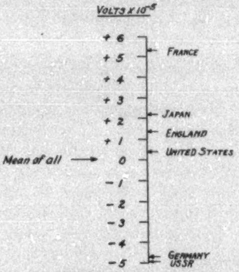
Standards for the international electrical units continue to receive attention at the National Standardizing Laboratories. These standards are the basis for electrical measurements of both the engineer and the physicist. The standards for the international system of units are essentially electrochemical and it is appropriate, therefore, to review briefly the present situation in regard to them. Since 1911 fundamental measurements of current have been based upon wire resistances and the value determined for the Weston normal cell by an international technical committee which did its experimental work in Washington during the year 1910. At that time values to be assigned to the wire resistance coils were agreed upon. No detailed specifications for either the standard cells or the silver voltameter which serves as the international standard for the measurement of current were agreed upon, but the work of preparing such specifications was continued by several of the national laboratories until interrupted by the War and a high degree of uniformity was attained in the voltameter measurements.

The interlaboratory comparisons of standard cells were also interrupted by the War and it is only within recent months that we have obtained comparisons of the value of the volt in the principal countries. Direct exchange of standard cells has been made between the Bureau of Standards and several foreign laboratories. Several groups of cells have been taken also to the various national laboratories by representatives of the Central Chamber of Weights and Measures at Leningrad. A report by M. Malikoff and M. Kolossof has recently communicated the results of their comparisons. On the basis of their report as well as the direct exchange of cells, the accompanying figure has been prepared to show the relation of the volt in six countries at the present time.

The maximum differences are rather larger than was to be expected. This should not be interpreted as meaning that the saturated cell is not reliable or reproducible since the value for the cell is a derived value and may therefore include uncertainties in the value of the ohm or errors in the use of the voltameter, or whatever other means may have been employed for determining the cell values from time to time.

The procedure for maintaining the volt by means of the Weston normal cell at the various laboratories differs very greatly. A redetermination of the international ampere by means of the silver voltameter has been undertaken by the Bureau of Standards. Work of this character has not been done previously for 15 years.

Whatever the outcome of the present discussions as to the advisability of continuing the international system of electrical units or changing to the absolute, c. g. s. system may be, the maintenance of the reference standards, particularly the standard cell and the wire standards for resistance will be none the less important. If the absolute units are eventually adopted in place of the present international system, the silver voltameter and the mercury ohm will be discarded.



RELATIVE VALUE OF THE VOLT IN SIX COUNTRIES AT THE PRESENT TIME

The fifty-third meeting of the American Electrochemical Society included a symposium on the chemical production of electricity. Eighteen papers were presented on primary cells, storage batteries, rectifiers, and electrolytic condensers. The feasibility of making dry cells without the use of manganese ore was described in several papers. Graphitic oxides have become a commercial possibility as a substitute for manganese dioxide, but no immediate change in the construction of dry cells is likely. The graphitic oxides, however, should find other applications where a convenient source of loosely held oxygen is needed. The absorptive properties of finely divided carbon have also made possible the construction of primary cells of large capacity, subject only to the renewal of the zinc and the electrolyte.

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*COMMITTEE ON ELECTROCHEMISTRY AND ELECTROMETALLURGY:

G. W. Vinal, Chairman.

Lawrence Addicks,
A. N. Anderson,
T. C. Atchison,
Farley G. Clark,
Safford K. Colby,
E. B. Dawson,
F. A. J. Fitzgerald,
W. E. Holland,
F. A. Lidbury,
C. G. Schluederberg.
J. A. Sede,
Magnus Unger,
John B. Whitehead,
J. L. Woodbridge,
J. L. Yardley.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

The development of satisfactory aluminum electrolytic condensers has been important in the telephone field. These condensers have a service life yet to be determined. Some have been in service more than five years and others, operating under test conditions in the laboratory, have passed eight years. The capacity depends somewhat on the formation and the conditions of service. Condensers for 24-volt circuits have a nominal capacity of 1000 $\mu$ f. and weigh about 40 lb.

An electrical distillation method described in a recent paper before the Electrochemical Society has been developed for the manufacture of chemically pure hydrochloric and nitric acid. By this means a continuous process has become possible, utilizing electrical energy in place of fuel, with added advantages of greatly reduced cost and an improved product.

Electric melting of steel and iron has maintained its already established position. Complete data are not available on furnace installations during the past year, but a considerable number of new installations include the 'Lectromelt furnaces. The United States is believed to lead the world in the production and utilization of the electric furnace. One noteworthy installation for which an order has been placed during the early part of 1928 is for a 60-ton steel-melting furnace to have an installed transformer capacity of 20,000 kv-a. The phrase "electric steel" has now become a trade mark of superior quality.

Increasing interest has been noted in the possibility of providing greater uniformity in composition and physical properties of cast iron and this affords a promising field for electric furnaces.

The induction type of furnace, sometimes referred to as the high-frequency furnace, has appeared in the ferrous field for the production of alloy steels. In the past, the opinion has been held that the induction furnace would not be useful in the iron and steel industry although it had found a place for itself in the nonferrous field. At the present time some are inclined to think that the widest application for the induction furnace will eventually be in the iron and steel industry. The design of a one-ton steel melting furnace of the induction type is now in the development stage. During the past year new installations have been devoted largely to the manufacture of high-grade special steels and alloys.

Another development in the electric furnace field has been the introduction from France into this country of the Miguet electric furnaces. Electric furnace engineers have recognized the desirability of using large electrodes in order to produce more efficient operation and better quality of production. The electrode in the Miguet furnace covers the entire molten charge, that is, the diameter of the electrode is equal to the diameter of the bowl.

Electric melting in the brass industry is a development of comparatively recent years but it has now become firmly established by affording a control of the product that was previously lacking and by improving working conditions. The smaller brass foundries have been somewhat slower in adopting electric heat for melting than the larger plants in the wrought brass industry, but relatively small furnaces of the single-phase type are now becoming more common.

Increased interest has been shown in the wide application of electric furnaces to various other industries and of particular note is the recent application of electric furnaces to glass melting. This has been a difficult problem to which extended research has been devoted and it is only recently that practical installations have been made. The glass charge is used as the resistor.

Industrial electric heating and annealing has continued to advance. Recent conferences on this subject have been held at Purdue and Yale Universities. A notable example of electric heating and annealing has recently been carried out at the Bureau of Standards in connection with the cooling of the largest disk of optical glass ever cast in America. Refractories for furnaces used in the glass industry have been improved during the year by the introduction of Corhart cast refractory blocks. These are made by fusing aluminous silicious material in an electric furnace and then casting the material in blocks at a temperature about 1900 deg. cent. This material on cooling has a dense interlocking crystalline structure which is nonporous. Tests which have been made in the glass industry show that it has much longer life than any other refractory previously used in that work.

Among the resistors for furnaces, there has been further development in what is known as the Globar elements. These elements are made of silicon carbide. The idea of using this material as an electrical resistor in high temperature work is not new, but it has not been used extensively until recently. Silicon carbide has a large negative temperature coefficient and when used as a resistor was not entirely stable. That is, its resistance tended to increase after a short period of use. During the past year a much more stable resistor of this type has been made and these are now obtainable in large sizes, some as large as 2½ in. in diameter and 5 ft. long with an electrical rating as high as 25 kw. per bar. Another difficulty with these resistors has been overcome by a method developed within the past year for improving the electrical contact at the terminals.

Chromium plating continues to be the center of interest in the electroplating field. Clearing of the patent situation will doubtless further stimulate the use of this metal in electrodeposition. One of the most interesting developments during the past year has been in connection with chromium plated tools. The industry has reached a stage where the demand for chromium plated-ware is far in excess of the supply.

Cadmium plating is proving valuable as a preventative of rust and its use is growing on this account.

Many attempts have been made to develop satisfactory methods of electroplating aluminum and its alloys, but few of these hitherto described have been successful. Adherent smooth deposits of nickel and other metals on a roughened aluminum surface have now become possible by methods recently described to the Electrochemical Society. These methods vary in detail and are adapted to pure aluminum as well as to each of a number of its alloys. The plated aluminum has advantages by reason of its improved appearance as well as its resistance to abrasion.

The Copper and Brass Research Association has been instrumental in making the uses for copper and brass better known to the public. Evidence of this is found in the fact that the use of brass pipe has increased over 200 per cent in the last three years. The older copper refineries are said to be planning extensive modernization programs chiefly along the line of reducing the power cost.

The output of electrolytic zinc continues to grow as a result of available cheap zinc concentrates which can be handled by this method. This affords a valuable outlet for electrical energy which is likely to increase. The output of electrolytic zinc from aqueous sulphate solution is estimated at the present at 500 tons a day as compared with 100 tons at the close of the War. An increased capacity for the production of electrolytic zinc is forecast for the coming year as several large electrolytic plants have recently been built or projected and some chemical engineers say the time is not far distant when virtually all zinc will be electrolytically refined, as in the case of copper, because of the better quality of the product. The development of the de Laval electrothermic process in Sweden by American interests may, however, have an important result in this field.

In the lead field, additional Betts plant capacity is being built and it seems possible that the demand for lead which is very low in bismuth may become more general. At Kellogg, Idaho, and in Peru, the Tainton process of recovering lead electrolytically from leach liquors along lines analogous to the zinc work is in development.

In the field of aluminum and its alloys a new form of sheet material combining the strength of the alloy and the resistance to corrosion of pure aluminum has recently appeared under the name, Alclad. This consists of a heat treated aluminum alloy base with a smooth nonporous surface of pure aluminum alloyed to the core. This material is expected to overcome serious difficulties which have been experienced with aluminum alloys in the past. Magnesium is finding increasing use in the aluminum alloys of high strength. Uses for the very pure aluminum prepared by the Hoopes process are increasing.

The chief interest in the production of metals from fused electrolytes has recently centered around the large aluminum plant now being constructed at Arvida, Canada. The capacity of this plant is planned to equal the present world production of aluminum. Two sections of the plant have been put in operation. The construction of all-metal airplanes is expected to be an important factor in providing an outlet for the greatly increased production of the light metals.

Beryllium has risen to a position of importance among the metals produced from fused electrolytes. Three per cent of Beryllium added to iron produces a steel and an equal quantity added to copper makes a valuable bronze. Rare metals are being produced on a limited scale by the electrolysis of fused salts and of these the most notable is probably Zirconium.

The use of electrolytic hydrogen in the production of synthetic ammonia has been increasing. Several large installations are planned for this year in Japan and Norway. One of the objections in the past to the electrolytic manufacturing of oxygen has been the lack of a market for the byproduct, hydrogen. The use of atomic hydrogen in welding operations promises a possible balance to make possible the economic production of electrolytic oxygen and hydrogen in place of liquification equipment now used for making oxygen alone.

A new type of oxy-hydrogen cell has recently been designed to operate at high temperatures without undue deterioration. The larger cells are rated for 2.3 volts at a maximum current of 15,000 amperes. These cells are said to be able to follow the normal load in somewhat the same way as the storage battery when charging at a variable rate and to do this without any great change in efficiency. Off-peak energy converted to direct current can be absorbed with a consequent improvement in load factor and it is claimed that the cells may be operated on 3300-volt circuits. It is suggested that under some conditions the large scale production of these gases at a low cost might reach a point where they could be used in the production of gas for heating purposes.

The materials for nitrogen fixation are so universally available that the problem of nitrogen fixation and the use of the products for fertilizer, munitions, or otherwise is largely a problem of national requirements, as to which each nation can reasonably hope to be independent. The development of nitrogen fixation, however, depends on the economic conditions and is in the line of decreasing cost of production wherever possible. Electric power is not available cheaply enough to make the arc process a likely competitor of the other processes. The synthesis of ammonia is developing most rapidly at present.

The great development in small rectifiers of the electrolytic type which was noted several years ago in the radio field has been checked by the recent development of a-c. radio sets and the so-called dry or electronic rectifiers. Valuable information as to the details of improvements made in the aluminum rectifier as well as other types have become available. Mechanical rectifiers for high-voltage alternating current have been displaced by the vacuum tube.

In the field of electrochemistry of gases, outstanding developments are largely the researches of Dr. Lind and his associates who have been able to produce reactions at low temperatures without use of high voltages by exposing the gases to the emanations from radium. Similar work has been done by Daniels and others on the synthesis of ozone and nitric oxide by the use of high-voltage cathode rays. The use of ozone for the purification of drinking water has trebled within the past few years.

Outlets for electrical energy in various industries that have not previously made extended use of electricity are significant. In the paint, varnish, and lacquer industries the electrolytic production of lead carbonate is increasing. The synthetic preparation of acetic acid, acetone, and methyl alcohol in which electrolysis may play a part, has had an important effect in replacing products formerly obtained by wood distillation.

The heavy clay industry has made progress in the use of electrical machinery but is still behind in the development of such lines. Brick manufacturers are beginning to realize the advantages of electricity as a means of saving labor and the proper control of the products.

On all sides we find a constantly increasing demand for new products to meet conditions which were unknown in the past. Everywhere there is an increasing interest in the work of the research laboratories and the demand for greater results from research people.

The committee wishes to acknowledge valuable suggestions for the preparation of this report which have been made by Prof. C. G. Fink, secretary of the American Electrochemical Society.

George W. Vinal, *Chairman.*

# Electrical Machinery

## ANNUAL REPORT OF THE COMMITTEE ON ELECTRICAL MACHINERY[*]

*To the Board of Directors:*

At the beginning of this year, the Electrical Machinery Committee adopted a new plan of organization, comprising apparatus subcommittees to deal with matters in their respective fields, and, in addition, two general subcommittees, one responsible for the preparation of the annual report and the other responsible for the review of papers submitted to the Institute.

Each apparatus subcommittee has dealt with such matters as the initiation of papers, collection of information for use in the annual report, the development and publication of useful information, and the initiation and preparation of Institute standards in cooperation with the Institute Standards Committee.

Five apparatus committees have been organized during the year as follows: Transformer with W. M. Dann, Chairman; Synchronous Machinery, W. J. Foster, Chairman; Induction Motors, P. L. Alger, Chairman; D-c. Generators and Motors, A. M. MacCutcheon, Chairman; Mercury Arc Rectifiers, B. G. Jamieson, Chairman.

The chairman of each subcommittee has organized a committee whose membership has included members from the Electrical Machinery Committee and members from the Institute at large. While the membership of the Electrical Machinery Committee has been somewhat smaller than in previous years, there has been no limit placed upon the size of the several apparatus subcommittees. Each chairman has changed and increased the membership of his subcommittee as the nature of the work to be done has changed and increased.

The general committee on the annual report has consisted of C. W. Kincaid, chairman, and the chairmen of the various subcommittees. While the chairman of the annual report subcommittee has been responsible for the preparation of the annual report, he has looked to the chairmen of the several apparatus subcommittees for material within their respective fields.

The general subcommittee on meetings and papers has been headed by the chairman of the main committee, and he has called upon the entire membership of the committee for help in reviewing papers submitted by the Institute's Meetings and Papers Committee.

According to this plan of organization, the work of the committee has been subdivided among the various subcommittees, and whatever has been accomplished by the Electrical Machinery Committee has been due to the initiative, sense of responsibility, and hard work of the subcommittee chairman. The chairman of the main committee wishes to take this opportunity of acknowledging the value of its work and expressing his appreciation of the large measure of responsibility they have assumed.

The committee has held two general meetings during the year—one in October and another in February during the Winter Convention. In addition to these general meetings, the various subcommittees have held separate meetings as required by their programs. In general, the detail active work of the committee has been accomplished through the meetings and other activities of the subcommittees.

The transformer subcommittee under the chairmanship of W. M. Dann has completed very important work in connection with transformer standards. An appendix to Transformer Standards, Section 13 of the Institute Standards, has been agreed upon and submitted to the A. I. E. E. Standards Committee for their consideration and action. This appendix covers recommendations for the *operation* of transformers by total observable temperature, and permits the operation of transformers at loads greater than the rated load providing the temperature of the cooling medium is below 30 deg. for air or 25 deg. for water.

The transformer subcommittee has also had in preparation recommendations for standards of constant-current transformers. This work has been done under the immediate direction of H. C. Louis.

The synchronous machinery subcommittee, under the chairmanship of W. J. Foster, has cooperated with the Institute's Standards Committee and with the Sectional Committee of the A. E. S. C. in the revision of Section No. 7 of the Institute Standards. This subcommittee has in preparation recommendations for standards on capacitators.

The subcommittee on mercury arc rectifiers, B. G. Jamieson, chairman, has been particularly active in initiating standards for this new type of apparatus and in collecting information concerning the application and operation of rectifiers in this country and in Europe.

During the year, 17 papers have been presented under the auspices of this committee at the general and regional meetings of the Institute. These papers and the discussions resulting therefrom have made valuable contribution to design information on such subjects as the reactance of synchronous machines, turbine generators, magnetic leakage and fringing flux, eliminating corona around armature coils of high-voltage machinery, methods of measuring cooling air, heat losses in the conductors of d-c. machines, excitation systems, and to the application information of two-pole synchronous motors, large frequency changers, etc.

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P. L. Alger,
B. F. Bailey,
B. L. Barns,
W. M. Dann,
W. J. Foster,
C. M. Gilt,
H. M. Hobart,
B. G. Jamieson,
A. H. Kehoe,
C. W. Kincaid,
H. C. Louis,
A. M. MacCutcheon,
V. M. Montsinger,
E. C. Stone,
R. B. Williamson.

*Presented at the Annual Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

The following review of progress during the past year has been prepared by the various subcommittees having jurisdiction over the particular machinery involved under the general direction of C. W. Kincaid. An attempt has been made in this report to include the more important articles that have appeared in domestic and foreign journals. These appear in several bibliographies and there are undoubtedly articles of real merit which have been overlooked. The committee will welcome having such omissions brought to its attention. A new plan has been initiated in connection with the bibliography in this annual report. It has been the endeavor to include all important articles and papers published during the calendar year of 1927 and, in addition, the outstanding papers that have been published in 1928 up to the time of publication. Next year's report will give a complete bibliography for 1928, repeating the more important references included in this report. By this plan the complete bibliography will be for calendar years (thus agreeing, as to dates, with the bibliographies prepared by leading libraries) and in addition, recent important articles and papers will be included.

### TRANSFORMERS

Very few engineers, with the exception of those intimately connected with the design of transformers, realize the remarkable changes that have been made in the design requirements during the last five years. With this in mind, we attempt to review in this report the factors that have brought about these changes and to show their effect on the developments of the past year.

These factors have been brought about by the natural growth and the changing requirements of the electrical industry which are due to the increase in capacity of power plants and substations, the extension of high-voltage transmission to higher voltage and greater power concentration, and the development of what can be properly termed high-voltage distribution networks.

These changes are responsible for the further development of the load ratio control transformer, the multi-winding transformer, and the varied winding auto-transformer. Such a unit not only steps up and steps down the voltage, but is frequently the meeting point of three or four voltages on the network, thus requiring three or four windings instead of two. Modern conditions also require that the voltages on various parts of a network be varied with the load. Thus it is no longer correct to speak of a "static" transformer. Gears, tap changers, and interlocking and remote control devices have been added for giving out and taking up the voltage slack of the system automatically as the load requires.

Then, too, the high-voltage distribution has resulted in many transformers with secondary windings of relatively high voltages. The 33-kv. secondaries have been quite common for some years. Now 66-kv. secondaries are often called for. Units are being built for 132 or 220-kv. to 66-kv. Even 110-kv. secondaries are appearing, and a bank with 140 kv. on both primary and secondary with load ratio has been built. This condition of having both windings at high voltages, of course adds to the physical size of a unit for a given kv-a. and since taps are frequently required in the secondary winding, they add to the difficulty of designing the unit.

There is one other factor that is of sufficient importance to mention. This high-voltage distribution with its increase in length of feeders has resulted in requirements for greater tap range in voltage due to the higher reactance of the feeders. Thus the customary 10 per cent range in voltage is no longer adequate for every condition, and tap ranges from 15 per cent to 20 per cent are being specified by some operators. This requirement adds to the size of the transformer and unbalances the design for it is practically impossible to maintain a balanced arrangement of the windings with respect to one another, except on one voltage connection. The unbalance increases with the tap range. Thus the larger the tap range, the greater the unbalance, the greater the change in reactance, and the greater the increase in short circuit forces.

### EQUIPMENT FOR CHANGING TAPS UNDER LOAD

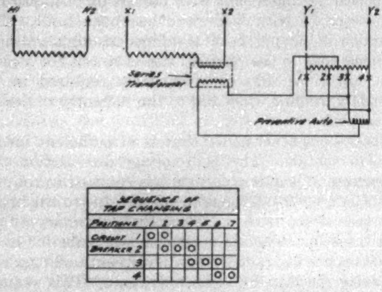
The report for 1926 describes in detail two methods of tap changing under load; namely, the two winding and the single winding arrangements.

During the year 1927, a large number of power transformers has been supplied with equipment for changing taps under load, with the ratio of the transformers changed by changing the voltage of a series transformer excited from a third winding on the core of the power transformers. This method permits the application of low-voltage tap changing equipment to high-voltage delta-connected windings and to high-voltage star-connected windings which are not grounded or to be grounded through a resistance.

Fig. 1 is a typical diagram of connections for this method of tap changing. A series transformer is connected in series with the winding whose voltage is to be regulated. One side of the primary of the series transformer is connected to the midpoint of the regulating winding, the other side of the primary winding being switched along the taps of the regulating winding by means of the tap-changing equipment. The familiar single-winding method is used for changing taps of the regulating winding. When power transformers are supplied with a third low-voltage winding for power purposes, taps can be placed on this third winding for use with the tap changer at only slight additional expense.

Three of the 10,000-kv-a. transformers shown in

Fig. 2 are used in a bank to transform 30,000 kv-a. from 140,000 to 140,000 volts, with equipment on one side for changing taps under load. Oil-immersed contactor switches are used to change taps by the single-winding method. Since the high-voltage winding whose voltage is regulated is connected in delta, a series transformer is connected inside the delta and is excited from a low-voltage tertiary winding. The tap-changing equipment is placed in the low-voltage winding.



| Positions | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Circuit 1 | ○ | ○ |  |  |  |  |  |
| Breaker 2 |  | ○ | ○ | ○ |  |  |  |
| 3 |  |  |  | ○ | ○ | ○ |  |
| 4 |  |  |  |  |  | ○ | ○ |

FIG. 1—SCHEMATIC DIAGRAM OF CONNECTIONS FOR CHANGING TAPS UNDER LOAD, USING A SERIES TRANSFORMER IN THE WINDING WHOSE VOLTAGE IS TO BE CHANGED AND THE REGULATING WINDING IS A THIRD WINDING ON THE SAME TRANSFORMER

What is thought to be the world's largest self-cooled transformer has recently been completed. It is rated at 33,333 kv-a., 220,000 volts star, to 69,000 volts star, to 13,200 volts delta. Seven of these units (one a spare) will be used to form two 100,000 kv-a. transformer banks at the Plymouth Meeting substation of the Philadelphia Electric Co. Power generated at the new Conowingo hydroelectric plant will be stepped down from 220,000 volts through these banks for transmission through the present 69,000-volt Philadelphia system. The 13,200-volt windings will supply two 44,000-kv-a. synchronous condensers for line regulation.

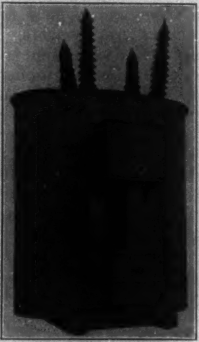


FIG. 2—10,000-KV-A. POWER TRANSFORMER—60 CYCLE—SINGLE-PHASE—140,000/140,000 VOLTS, WITH LOAD RATIO CONTROL EQUIPMENT MOUNTED ON THE SIDE. CONNECTIONS AS SHOWN IN FIG. 1, WITH OIL IMMERSED CONTACTORS ARE USED

These transformers while rated at 100,000 kv-a. per bank have three separate windings, with equivalent parts somewhat higher. With auxiliary cooling on the radiators, which is contemplated in the future, the equivalent two-winding loading which the transformers will deliver with low ambient temperatures is 200,000 kv-a. per bank.

Each transformer complete with oil weighs 180 tons and occupies approximately 500 sq. ft. of floor space. Some idea of the height of the tank is obtained by the fact that a six foot man can stand underneath the fourteen foot radiators as they are mounted on the tank. The height over the high-voltage bushing is 31 ft.

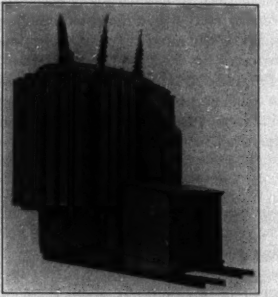


FIG. 3—33,333-KV-A. POWER TRANSFORMER—60 CYCLE—SINGLE-PHASE—220/69/13.2 KV. WITH LOAD RATIO CONTROL FOR THE 69-KV. WINDING

The construction used made it possible to ship the transformers in oil to their destination, notwithstanding the large capacity and high voltage.

These transformers are provided with equipment for changing the voltage ratio of the middle voltage winding by means of tap-changing equipment located in the low-voltage winding. Only one extra tap is necessary for the tap-changing equipment, as the low-voltage taps, which are used for the starting of the synchronous condensers are used for the tap-changing equipment. The single-winding method of tap-changing is used, with a type *UB* tap changer and preventive auto-transformer and series transformer. The preventive auto-transformer is switched along the low-voltage taps by means of the circuit breakers of the type *UB* tap changer. The midpoint of the preventive auto-transformer and the midpoint of the low-voltage winding are connected to the primary of the series transformer, the secondary of the series transformer being connected in series with the middle-voltage winding to give a voltage regulation of 15 per cent in six 2½ per cent steps. Fig. 3 shows this transformer and equipment.

Fig. 4 shows a 10,000-kv-a., single-phase, 35,000-volt transformer arranged for 20 per cent regulation, using a new type of tap changer of the single-winding method. Fig. 5 shows the scheme of connections in which the series transformer is connected in the line to be regulated and the primary of the transformer is excited from a low-voltage winding which in turn may be excited from any of the transformer windings. Only two tap-changing circuit breakers are used, an auxiliary oil-immersed tap-changing switch being used to do the actual tap-changing. One of these transformers is arranged for complete automatic control in response to fluctuation of the system voltage.

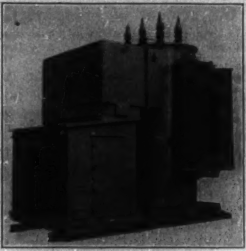
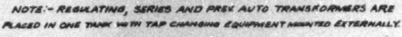


Fig. 4—10,000-Kv-a. Power Transformer—60 Cycle—Single-phase—35,000 Volt, with Control for 20 Per Cent Voltage Regulation, Using the Scheme of Connections Shown in Fig. 5


SERIES TRANSFORMER
PREV. AUTO
A
B
1
2
3
4
5
SEPARATE REGULATING TRANS.
NOTE:- REGULATING, SERIES AND PREV. AUTO TRANSFORMERS ARE PLACED IN ONE TANK WITH TAP CHANGING EQUIPMENT MOUNTED EXTERNALLY.

| SEQUENCE OF TAP CHANGING | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| POSITION | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| SWITCH-1 | ○ | ○ | | | | | | | | |
| 2 | | ○ | ○ | ○ | | | | | | |
| 3 | | | | ○ | ○ | ○ | | | | |
| 4 | | | | | | ○ | ○ | ○ | | |
| 5 | | | | | | | | ○ | ○ | |
| CIRCUIT A | ○ | ○ | | ○ | ○ | ○ | | ○ | ○ | |
| BREAKER B | | ○ | ○ | ○ | | ○ | ○ | ○ | | |

○ CIRCUIT BREAKER AND SWITCH CLOSED

Fig. 5—Schematic Diagram of Connections for Changing Taps Under Load Using a Series Transformer and a Regulating Winding, both of which May be in the Same Winding

Fig. 6 shows tap-
20,000-kv-a., three
of separate regulat
former, which is exc
of the main transf
are mounted in a sep
ing equipment is atta

Another interesti

Fig. 6—20,000-Kv-a
with the Series Tran
Mounted in a Separa
Equipment is Attach

Fig. 7—6850-Kv-a
66,000/60,000 Volts w
by Means of Taps a

three-phase, O. I.
former with type
43 per cent voltag
kv-a., single-phase
across taps of the tr
age regulation over
ber of operating vol
tion regulator to c
have a capacity o

-changing equipment applied to ten
ee-winding transformers by means
ating units. The regulating trans-
xcited from the low-voltage winding
former, and the series transformer
eparate tank to which the tap-chang-
tached.

ting development is a 6850-kv-a.,

-A. Three Winding Power Transformer
ansformer and Regulating Transformer
rate Tank to Which the Tap-Changing
ched

-A. Three-phase Power Transformer
with 43 Per Cent Voltage Regulation
and Induction Regulators

. S. C. 66,000- to 60,000-volt trans-
*UR* tap-changing equipment to give
ge regulation under load. Three 60-
se induction regulators are stepped
transformer to give smooth curve volt-
r the entire range with an infinite num-
oltage positions. A three-phase induc-
cover the same range would have to
of 1400 kv-a. The equipment is so

designed to be applicable to larger kv-a. transformers merely by the substitution of larger kv-a. regulators, and is built for future addition of automatic control which is responsive to voltage fluctuations of the system. Fig. 7.

### THE INERTAIRE TRANSFORMER

In addition to the 33,333-kv-a. transformers for Philadelphia Electric Co., four 33,333-kv-a., O. I. S. C. Inertaire transformers for Southern California Edison Co. have been built. These transformers will be installed in a 100,000-kv-a. bank, with a spare, at Long Beach Steam Plant No. 3, to operate on a 220-kv., three-phase, 50-cycle system transforming from this voltage to 16,500 volts on the low-voltage winding.

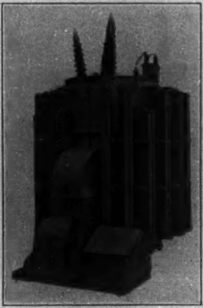


FIG. 8—33,333-KV-A. INERTAIRE POWER TRANSFORMER 220,000/16,500 VOLTS, 50 CYCLES. EQUIPPED WITH AUXILIARY AIR COOLING ON THE RADIATORS

These transformers are two-winding units arranged with detachable radiators equipped with duct for air blast. Complete with blower equipment these units will each weigh approximately 98 tons and occupy a floor space of 360 ft. Over-all height from rail to bushing tip, approximately 32 ft. They will carry 60 per cent normal load continuously with an ambient of 40 deg. cent. without exceeding 55 deg. cent. when the blowers are not in operation. Blowing equipment is individual and mounted on separate base with wheels. By opening the duct at one point, complete blower equipment can readily be moved away from the main units.

The motors for this equipment are of the across-the-line starting characteristics. All motors, including spare unit, are arranged to be started and stopped together by relay actuated by temperature conditions inside the main transformer. These transformers are shown in Fig. 8.

In the Inertaire transformer, the breathing regulator allows in-breathing at a slight vacuum but prevents out-breathing until a pressure of 5 lb. is developed in the transformer tank. Thus there is a definite relation between the amount of initial gas space required and the change in oil volume to keep the transformer from breathing.

With small transformers this relation can be obtained with a reasonable initial gas space, but as the size of the transformer increases, with its consequent reduction in gradient between copper and oil, it becomes desirable to decrease the amount of breathing by providing additional gas space to supplement the volume above the oil level.

During the past year it has become customary to supply on all large transformers some additional gas space other than that above the oil, in order to cut down the amount of breathing of the transformer. This decrease in breathing reduces considerably the cost of maintenance of the Inertaire equipment for the chemicals of the Inertaire jars are used up in proportion to the amount of breathing which takes place.

Several methods are used to obtain this additional gas space.

The general practise, as shown in Fig. 9, is to place gas chambers beneath the oil level between the iron core and the tank. These are crescent-shaped compartments welded to the tank wall with or without a space between, depending upon the type of transformer. In a few cases ordinary expansion tanks have been supplied, filled with an inert gas and connected to the gas space in the transformer tank. These act as gas chambers and cut the breathing of the transformer down to a minimum. Another type of gas chamber consists of connecting a spare tank to the gas space of one or more transformers, and this auxiliary space provides the necessary gas space to prevent the transformer from breathing. In this way the maintenance cost of the Inertaire transformer in extremely large sizes which ordinarily breathe large volumes of air has been greatly reduced.

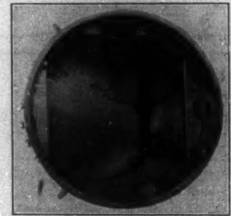


FIG. 9—INTERNAL TANKS TO PROVIDE MORE SPACE FOR EXPANSION OF INERTAIRE AND THUS REDUCE THE AMOUNT OF BREATHING

There are approximately 85 different operating companies now using Inertaire transformers, with a total Inertaire transformer capacity of about 5.5 million kv-a. in service.

### DISTRIBUTING TRANSFORMERS

During 1927 a number of three-phase, 60-cycle, O. I. S. C. manhole transformers of 300- and 450-kv-a. capacity were built. These transformers take power at approximately 11,000 volts, delta, and supply the low-voltage network at 199 volts star with a permanently grounded neutral for four-wire operation.

Each transformer is fitted with the usual thermometer, oil-gage, drain, filter and sampling valves, and in addition, due to the possibility of vaults or manholes being flooded with water, each transformer is fitted with a high-voltage and low-voltage pothead to which lead-covered entrance cables can be attached. A three-phase tap changer in the high-voltage winding is also used and controlled by a single hand-lever, operated outside of the tank. In addition, the high-voltage side of the transformer is fitted with a three-way disconnect and grounding switch such that the high-voltage line can be open or it can be connected to the transformer or solidly grounded for protection when necessary to do any work on the unit. This switch is operated outside of the tank and can be padlocked in each position. Inside the tank is an electrical interlock which automatically locks this switch when the transformer is energized.

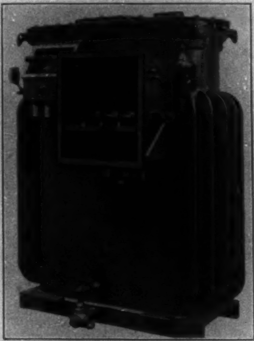


FIG. 10—THREE-PHASE NETWORK TRANSFORMER EQUIPPED WITH JUNCTION BOXES AND CABLE DISCONNECTING AND GROUNDING SWITCH IN PRIMARY JUNCTION BOX. JUNCTION BOXES OPEN. SWITCH IN OPERATING POSITION

An all-welded boiler-iron tubular tank is used with the high-voltage and low-voltage potheads made as an integral part of the tank. Each tank has a structural steel base to facilitate any moving of the transformer during installation. Lifting eyes are provided to handle the complete transformer. (Fig. 10.)

### CURRENT TRANSFORMERS WITH NICKEL-IRON CORES

The errors in a current transformer are due to the characteristics of the core material used. When this material has high losses and low permeabilities, the errors will be much larger than when the material has low losses and high permeabilities. Research work has resulted in the development of a new magnetic material called Hipernik which possesses exceptionally low losses and high permeabilities.

By the further development of a special magnetic circuit, which permits fuller use of the exceptional qualities of Hipernik, current transformers have been developed in which the errors are practically negligible, and far less than heretofore possible to make them using silicon steel. The application of these transformers is not confined to any particular class of secondary burdens, but may be used with any type of secondary burden within the rating of the transformer. Fig. 11 shows the appearance of one type of transformer developed.

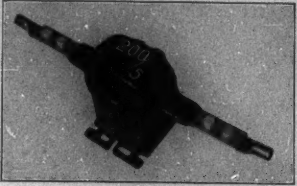


FIG. 11—PRECISION CURRENT TRANSFORMER USING HYPERNIK STEEL

Some current transformer units for use on 154,000-volt circuits were built during 1927. These are, so far as is known, the highest voltage instrument current transformers ever produced. Fig. 12 shows an interior view of one of these units.

The voltage limit in potential transformers was carried to a new figure in the manufacture of some units built for operating on a 220-kv. system in the East. Fig. 13 shows an external view of one of these transformers.

### A NEW TESTING OUTFIT FOR INSULATING OILS

The importance of keeping a careful check on the dielectric strength of oil used for insulation purposes is readily recognized. In most testing sets the variable high voltage necessary for testing oil is secured by switching a low voltage between taps on the primary side of the transformer. This method requires that the transformer be deenergized and then reenergized between taps. Such a method introduces distortions in the test voltage which lead to erroneous interpretation of the oil failure. A new method in which the transformer is energized at all times during an oil test has been devised and incorporated in a testing set shown in Fig. 14. In this set, the test voltage can be raised fairly smoothly without the introduction of transients;

hence, the voltage observed from the meter is a correct indication of the voltage at which the oil was tested.

The complete set is arranged in an aluminum case and can be carried in the same manner as a suitcase. It operates from an ordinary light socket at 110 volts, 60 cycles.

The a-c. high-voltage testing sets furnished during the year included complete equipment for several new laboratories. There were transformers, each rated 60 cycles, 300/600 kv-a., 250,000 to 1150/2300 volts and designed for chain connection to give 750,000 volts to ground. Individually, they are guaranteed for continuous operation and so far as known are the highest voltage units ever built for such service.

For use in making commercial tests on cables, there were built some 400-kv-a., 200,000-volt transformers, two of which were arranged in series to give 400,000 volts to ground.

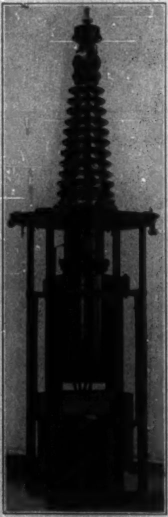


Fig. 12—Instrument Current Transformer for 155,000-Volt Circuit. 200/400 Amperes

One of the most complicated little testing transformers ever designed is one rated 60 cycles, 1.5 kv-a., 5010 to 110/220 volts, shown in Fig. 15. The high-voltage winding is so arranged that practically any voltage between 2 and 5010 may be obtained. Low reactance was specified and the measured impedance was 0.244 per cent.

### D-c. Kenotron Testing Sets

Two 400,000-volt sets, placed in service during the past year, gave the highest d-c. voltage so far used in commercial work. One of these installations is shown in Fig. 16.

There were several new equipments developed during the year, one, a 7500-volt set illustrated by Fig. 17, is unique in that it will be used for tests on 600-volt d-c. distribution feeders, a new application.

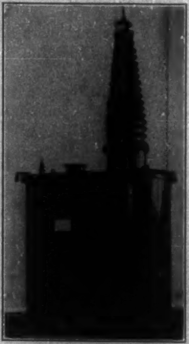


Fig. 13—Instrument Potential Transformer for 220,000-Volt Grounded Circuit

### Cable Entrance Junction Box Transformers

The development of higher-voltage cables, the desire of operators to avoid exposed connections, and especially the difficulty of making satisfactory end-bells, led to the adoption of transformers with cable entrances—the cable either terminating directly inside the transformer tank, or terminating in oil or compound-filled junction boxes which are connected to the transformer

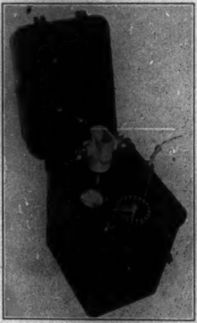


Fig. 14—Portable Testing Outfit for Checking the Quality of Transformer Oils

by means of bushings, both ends of which are immersed in oil.

Frequently, the necessity for routine testing of the cable requires means of readily disconnecting the cable from the transformer. To an increasing extent, disconnecting switches are fitted in the junction boxes with special testing bushings, so that the cable can be switched from the transformer to the testing connection or to the ground. Fig. 18 shows an installation of such transformers.

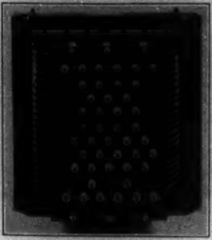


FIG. 15—LABORATORY VARIABLE RATIO TRANSFORMER, 1.5/5010 VOLTS

FIG. 16—INSTALLATION OF 400,000-VOLT D-C. CABLE TESTING SET

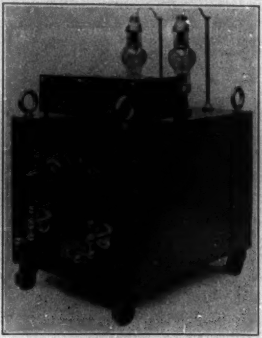


FIG. 17—D-C. CABLE TESTING SET. 7500 VOLTS END GROUNDED

A notable example of the adoption of this means of protection is found in the group of 20,000-kv-a., water-cooled transformers, furnished by one manufacturing company for the State Line Generating Company. These consist of 17 single-phase and 4 three-phase units, all of which receive current from the generator at 22,000 volts. The high-voltage ratings of seven of the single-phase units is 132,000 Y, the remaining ten being 66,000 Y, and three-phase units 33,000 Y. All these transformers are provided with cable-entrance bushings on the low-voltage side and all but the 132,000-volt units are equipped with cable-entrance bushings and self-contained disconnected switches on the high-voltage side. These transformers are also provided with load ratio control.

FIG. 18—INSTALLATION OF POTHEAD TRANSFORMERS WHICH COMBINE THE CABLE POTHEAD WITH THE TOP OF THE TRANSFORMER

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## SYNCHRONOUS MACHINES

The tendency toward larger machines in certain lines continued throughout the year 1927. This was true especially in connection with steam turbine generators, the sizes of which went up in erratic steps to 160,000 kw. for a single-shaft unit, and to 208,000 kw. for a three-shaft unit.

The trend in mechanical design was away from castings, so generally employed heretofore, since the first electrical machines were made, to the use of fabricated structures for practically all parts of the machine. These structures are made by welding together standard plates and standard structural shapes, such as beams, channels, and angles.

The trend in electrical design has been toward all possible reduction of losses and, consequently, attainments of higher efficiencies. The attack has been made, for the most part, on load losses, especially the losses in the mechanical parts due to stray fluxes.

Considerable thought has been given to the matter of improving the stability of machines by quick response excitation and superexcitation. A number of installations of such systems of excitation were in contemplation at the end of the year. Investigations and tests in the shops of various manufacturers were carried on.

## HYDRAULIC GENERATORS

There has been an increasing number of installations where automatic operation or distant control has been introduced.

Outdoor installation of hydraulic generators was often under consideration, but no important installation was made during the year.

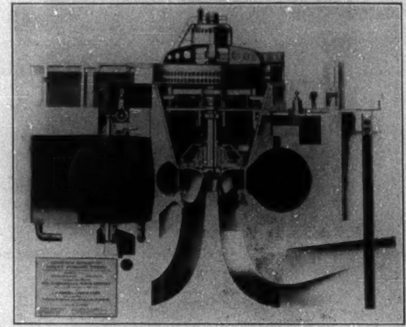

FIG. 19—SECTION THROUGH 40,000-KV-A. VERTICAL WATERWHEEL GENERATOR AND TURBINE

Great interest was shown during the year in the progress of the Conowingo Development on the Susquehanna River in the State of Maryland, under the direction of Stone & Webster, for the Philadelphia Electric Company, owners of the plant. The Annual Report of the Electrical Machinery Committee for 1926-27 gives considerable data on the generators, which are 40,000 kv-a., 81.8 rev. per min., 13,800-volt, 60-cycle machines. The present development consists of seven units; see Fig. 19, assembly in cross section of the combined wheel and generator. Six of these units were in operation June 1, 1928.

Both manufacturers introduced fabricated steel plate structures, but one of them used it to a greater extent. Practically the only parts of its machine that were made of castings are the upper bearing bracket and the hub of the rotor. Probably the most interesting and novel part of this generator is the rotor spider. Views of plate rim and arms are shown in Figs. 20 and 21.

At the close of the year one manufacturer reported a list of large hydraulic generators that had been put into operation, or had been made in its shops, or for which orders had been received during the year as follows:

2–45,000-kv-a., 50-cycle, 11,000-volt, 250-rev. per min. horizontal generators are the largest of their type yet undertaken;
4–29,000-kv-a., 12,000-volt, 60-cycle, 100-rev. per min. vertical generators, with direct-connected auxiliary generators which supply power for motor-generator exciter sets arranged for quick response excitation;
2–45,000-kv-a., 13,800-volt, 60-cycle, 400-rev. per min. vertical generators, with direct-connected exciter and pilot exciter;
2–45,000-kv-a., 13,200-volt, 60-cycle, 150-rev. per min. vertical generators;
2–22,500 kv-a., 60-cycle, 6600-volt, 120-rev. per min. vertical generators, with direct-connected exciters;
2–28,000-kv-a., 50-cycle, 11,000-volt, 300-rev. per min. vertical generators, with direct-connected exciters.

Another manufacturer reported installation and putting into service during the year two plants where the closed systems of ventilation were introduced. One of these is the low-head plant of the Louisville Gas & Electric Company on the Ohio River, which contains eight 12,550-kv-a. vertical 60-cycle generators running at 100 rev. per min., arranged for remote control. See Fig. 22. The other plant is that of the Washington Water Power Company, Lake Chelan, Wash., containing two 30,000-kv-a., 300 rev. per min., 60-cycle vertical units, the first one of which was put on the line during the fall.

Fig. 20—Assembled Rotor Run for 40,000 Kv-a. Conowingo Generator

The scheme of circulation of air is practically the same in the two plants. Eight water coolers are assembled at approximately equal intervals around the circumference, and arranged in pairs for circulating the air. In case of the smaller and lower-speed generator, all of the air passes into the pit underneath the generator and is driven out through the stator cores and windings by fans on the rotor, passing into the several sections of the stator frame and through the coolers, dropping down into conduits leading back into the pit. Every pair of coolers has an outside housing attached to the stator frame. In case of the larger and higher-speed generator, the outside housing is continuous, making a complete circle outside the stator frame, but the air into and out of every pair of coolers divides, a part of it passing upward and returning into the rotor via one of the four air pipes that connect into a common air chamber surrounding the top of the machine, and the rest of the air passes downward into conduits in the concrete foundation, and thence back into the rotor.

Fig. 21—Assembling Rotor Spider for Conowingo Generator

## STEAM TURBINE GENERATORS

Two or three European manufacturers of steam turbine units have designed or built 3000-rev. per min. generators with ratings as great as 37,500 or even 40,000 kv-a. The American manufacturers are more interested in 3600 rev. per min., or 60-cycle generators; 12,500 kv-a. generators of this speed were made during the year and 15,625 kv-a. was designed.

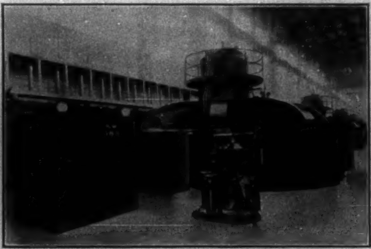

Fig. 22—Water-wheel Generators Showing Coolers Attached to Frame

The large 1800-rev. per min. generator mentioned in last year's report was installed and put in service during the year at Waukegan, Ill. It is rated 59,000 kv-a., 50,000 kw., 12,000 volts, and uses the closed system of ventilation with two external blowers and fin-type radiators. The operation of the generator has been satisfactory, especially in respect to quiet running and low temperature in both rotor and stator.

Skeleton types of stator frame, consisting of steel plate, welded or riveted, in place of castings, have been quite generally designed and built, especially for the largest generators. This construction results in machines that are not so limited by shipping facilities.

Among the more noteworthy large generators in process of manufacture is the cross-compound 188,000-kv-a. unit for the New York Edison Company, which consists of two 94,000-kv-a., 13,800-volt, 60-cycle, 1800-rev. per min. generators. These are the largest 1800-rev. per min. generators yet built. This unit is of special interest in that the separately driven fans for supplying the cooling air are the vertical type driven by 3600-rev. per min. induction motors, three fans in all, mounted between the generators. The air is discharged from the top of the generators into a common chamber from which the fans take it and pass it through the coolers back into the generators.

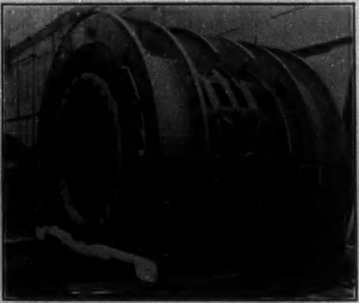

Fig. 23—Turbo Generator Stator with Ventilating Outer Skeleton Partly Assembled

Fig. 24—Hydraulic Bolt Puller for Tightening Through Bolts in Plate Type Turbo Rotor

This same company has extended the use of the skeleton stator frame to all large 1800-rev. per min. generators where shipping limitations require it. Fig. 23 shows a turbine generator with part of the superstructure installed.

This company has developed the plate rotor with forged shaft ends, and also has developed a hydraulic bolt puller for fastening together plates and shaft ends. A partial view of one of these rotors in the bolt-pulling machine is shown in Fig. 24. Two bolts can be pulled at the same time. The nuts are run on by hand after the plates are stretched, and this practise prevents thread friction and galling under the nuts. An improvement introduced during the year, in connection with built-up plate rotors, has been the making of the plates with holes in the center, in connection with which it has been found possible, by proper heat treatment, to raise the elastic limit on carbon plates from 23,000 to 55,000 lb.

During the year, the single-shaft generator units put into service by another manufacturer are as follows:

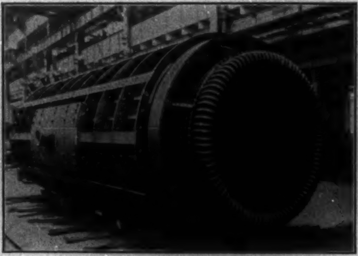

Fig. 25—Inner Skeleton Structural Frame for Turbo Generator

75,000-kv-a., 0.8-p. f., 1800-rev. per min. generator in the Edgar Station of the Boston Electric Illuminating Company, with direct-connected house service generator of 6250 kv-a., 0.8 p. f.;

A 55,000-kv-a., 0.9-p. f., 1800-rev. per min. generator in St. Louis. This generator has fans on the rotor and is at the present time the largest self-ventilated machine at 1800 rev. per min. that this company has built.

The first of this company's 22,000-volt generators was completed. It is 61,765-kv-a., 0.85-p. f., 1800-rev. per min. with direct-connected house service generator of 3571-kv-a., 0.7 p. f. It is to be installed in the Powertown Plant of the Superpower Company of Illinois.

The first of the two 100,000-kv-a., 1500-rev. per min., 50-cycle generators for the Southern California Edison was practically completed at the end of the year. The wound stator is shown in Fig. 25, while the outer stator frame is shown in Fig. 26.

Other single-shaft units in process of manufacture at the close of the year were a 66,667-kv-a., 0.9-p. f., 1800-rev. per min., 60-cycle generator, an 83,333-kv-a., 0.9-p. f., 1500-rev. per min., 25-cycle generator, and a 160,000-kv-a., unity power factor, 1500-rev. per min., 25-cycle generator. One of the features of the construction of the 160,000-kv-a. is the arranging of the stator winding as two entirely independent windings, each having capacity of 80,000 kv-a., connected through separate switches to adjacent bus sections. Two distinct advantages are to be obtained by this scheme; first, reduction in size of the individual switches; second, the elimination of bus reactors made possible by the transfer of power taking place through the coupling effect of the two separate windings.

In multiple-shaft units, it has nearly completed a 165,000-kv-a., consisting of three generators of practically the same rating for the American Gas & Electric Company, Philo Station. It also has begun work on a 208,000-kw. unit for the State Line Company consisting of one 89,412-kv-a. generator, and two 72,941-kv-a. generators, all at 1800 rev. per min. and wound for 22,000 volts.

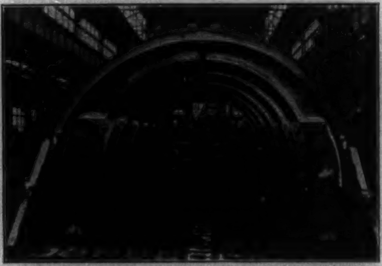

FIG. 26—OUTER SKELETON STRUCTURAL FRAME FOR TURBO GENERATOR IN FIG. 25

The advantages secured by the use of skeleton frame construction were set forth somewhat in detail in last year's report. They appertain chiefly to the matter of shipment. It has been found possible to design all three of the large generators in the 208,000-kw. triple-shaft unit State Line, with skeleton type frames, so that they may be wound at the factory and shipped complete, no outer frame or superstructure being required.

An advantage obtained by designing the stator frame with inner and outer parts like those shown in the photographs pertaining to the 100,000-kv-a., is the facility with which such machine may be made fit to contain some gas other than air in its ventilation system. There will be involved simply the removal of the outer frame and the substitution of a gas-tight structure of welded steel plates.

Additional tests in an atmosphere of hydrogen have been conducted during the year on the 6250-kv-a. generator mentioned in last year's report.

### MARINE TURBINE GENERATORS

During 1927 the two airplane carriers,—the *Lexington* and the *Saratoga*, were put into commission. They are the largest electrically-equipped ships afloat. Each has four 40,000-kv-a., 1755-rev. per min., 5000-volt generators. The motors, direct-connected to the propellers, are induction motors.

During the year the *SS. California*, plying from New York to San Francisco via the Panama Canal, was equipped, with a 48-cycle steam turbine generator, and synchronous motors. The ship is a large one of slightly more than 30,000-tons' displacement. The two turbine generators are rated 6600 kw. each, at 48 cycles. The reversible synchronous motors are 8500-hp. each, at nominal speed of 100 rev. per min. The speed of the ship is to be 18 knots with both turbines running.

### U. S. COAST GUARD CUTTERS

The economy of the centralized power plant has been adapted to the machinery now being installed in five U. S. Coast Guard Cutters. The machinery consists of a main turbine generator rated 2600 kw., a 3000-hp. synchronous propelling motor, condensing equipment, and electrified auxiliaries. In addition are two dual-drive units, each consisting of a high-speed turbine and gear, a direct-current generator, and a synchronous machine that is used either as a generator or a motor. Under the usual condition of operation the power for a-c. auxiliaries is supplied direct by the main generator and for the d-c. auxiliaries from the same source through the dual-drive unit. By this method of using the main turbine generator to furnish power for auxiliaries the total steam consumption has been materially reduced. During maneuvering or when the main unit is secured, all auxiliary power is supplied by the dual-drive unit, driven by its turbine.

### SYNCHRONOUS MOTORS

An increasing demand for synchronous motors was in evidence during the year. Undoubtedly it is safe to say that they are now being applied in certain cases where induction motors were formerly thought necessary. They are being introduced into steel mills where they were not formerly considered.

There was a decided demand during the year for "full voltage" or "across-the-line" starting. This has probably resulted from the fact that better starting torque efficiency has been introduced into synchronous motors by more skilful design, and to the fact that the systems on which they operate have become larger, relatively, to the individual motor.

For applications where the starting requirements are most severe such as driving large grinders in cement mills, as a rule, salient-pole machines have been furnished, many of them with double squirrel-cage starting windings, some with magnetic clutches, and some of the so-called "supersynchronous" type. The last-named consists of a motor with a stator that may revolve, and be brought up to synchronous speed with the rotor at rest, and with the clamps arranged to exert a braking effect on the stator to bring it to rest while the rotor comes up to full speed.

Another company has built during the year induction synchronous motors as large as 1500 hp. at 163 ⅓ rev. per min. Fig. 27 shows a 1500-hp. motor that has been in operation at the plant of the Atlas Cement Company. It starts like an induction motor with definite wound secondary and external resistance. After attaining rated speed, d-c. excitation at 50 to 60 volts is supplied from a small induction motor-driven set. Excitation required is, approximately, 500 amperes. It is to be noted that the windings in the rotor are much deeper than in an induction motor, since these windings serve as synchronous motor excitation windings.

### SYNCHRONOUS CONDENSERS

Quiet operation has been emphasized in connection with the placing of orders for many of the synchronous condensers built during the year. Two installations of 5000-kv-a., 750- or 900-rev. per min. condensers were made for the City of Los Angeles which were provided with the closed system of ventilation, containing radiator type of coolers mounted in the condenser foundation.

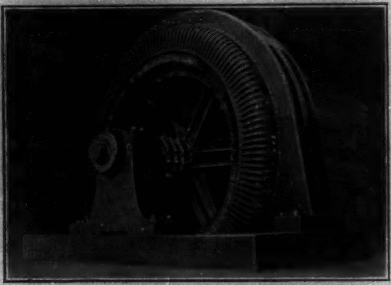

FIG. 27—1500-HP. 163⅓-REV. PER MIN. SYNCHRONOUS MOTOR FOR USE IN CEMENT MILL

It is interesting to note that during the year two of the 50,000-kv-a. synchronous condensers for the Southern California Edison Company were put into operation in two substations in Los Angeles. These large condensers also had the closed system of ventilation with air coolers underneath. It is probable that the purchaser of these condensers specified this method of cooling not so much on account of the reduction in noise as because they were machines of very large capacity at high speed, and also for the reason that he wished to equip the substations with carbon dioxide gas, or some other fire-extinguishing compound.

A 7500-kv-a., 900-rev. per min., 60-cycle condenser was installed in Malden, Mass., and a 10,000-kv-a., 900-rev. per min. in Springfield, Mass., both with closed systems of ventilation and air coolers. The reduction of noise to a minimum was the consideration in both cases.

Two synchronous condensers to be installed outdoors, and for hydrogen operation, were in process of manufacture during the year. The smaller of these, 10,000-kv-a., when operating in air, and guaranteed to be at least 12,500 kv-a. when operating in hydrogen, was completed during the year, but not tested at the close of the year, except to be filled with the most explosive mixture of hydrogen and oxygen. It exploded in the explosion-proof pit. This was done to make sure that no damage would be done to the structural parts of the machine in case of an explosion. Fig. 28 shows this condenser in the testing pit, with head removed, revealing the coolers, which are semicircular in shape and arranged two at each end.

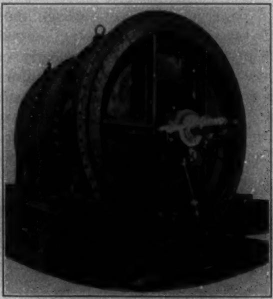

FIG. 28—HYDROGEN COOLED SYNCHRONOUS CONDENSER WITH END BELL REMOVED

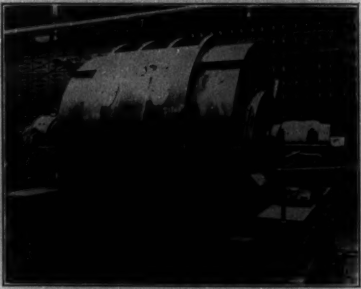

FIG. 29—7500-KV-A. SYNCHRONOUS CONDENSER SHOWING STRUCTURAL FRAME, END BELLS, AND BEDPLATE

Most companies are now building the 5000-, 7500-, and 10,000-kv-a., 60-cycle condensers at 900 rev. per min., instead of 720, thereby reducing weight, floor space required, and total losses.

Fig. 29 shows a 7500-kv-a. (condenser) with structural steel frame, end bells, base, sub-pedestals, etc.

Three 30,000-kv-a. condensers at 720 rev. per min. are now building for Philadelphia.

### FREQUENCY CONVERTERS

Nearly all frequency converter sets have synchronous machines at both ends. Probably the largest set of this type made during the year was a 29,400-kv-a., 25- to 60-cycle.

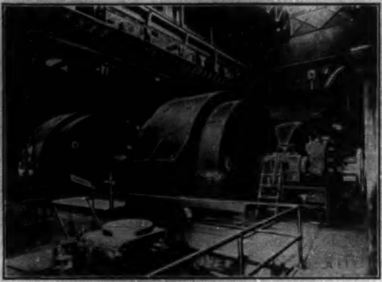

FIG. 30—21,400-KV-A., 25-CYCLE SINGLE-PHASE FREQUENCY CHANGER-SPRING MOUNTED

In cases where some flexibility in the voltage-tie between two systems is desirable, induction frequency converters may well be used. Such need may arise in the operation of synchronous converters, some of them from one of the systems, and some from the other, that feed direct current into common lines. Such a condition exists in New York City where large induction frequency converter sets have already been installed. Orders were placed during the year for two more 40,000-kw. sets.

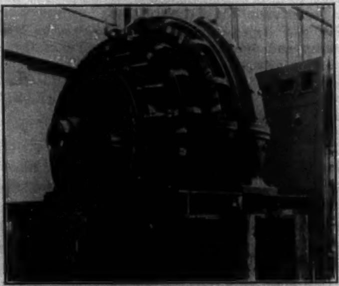

FIG. 31—4200-KW., 25-CYCLE SYNCHRONOUS CONVERTER

Fig. 30 shows a set rated 35,300 kv-a., three-phase, at the 60-cycle end, and 21,400 kv-a., single-phase, at the 25-cycle end, 13,600 volts. The 25-cycle end has a spring mounted stator frame. This set has been placed in operation in Philadelphia.

Orders have been placed for three 15,000-kw., 60- to 25-cycle sets for the same city. The rating of the 25-cycle, single-phase generator is to be 21,428 kv-a., 0.7 power factor. There have been furnished during the year two 60- to 25-cycle frequency changers for New Haven road, in which the 7140-kv-a., 25-cycle, single-phase generators had spring-mounted stators.

In certain cases, where the frequency converter serves as a tie between two systems, and is relatively small in comparison with the smaller of the two systems, Scherbius sets, or some equivalent that has flexibility in the frequency ratio, should be employed.

FIG. 32—4200-KW., 25-CYCLE SYNCHRONOUS CONVERTER. USING BENT SLAB FRAME AND ROLLER BEARINGS

Two sets of this type were being installed at the end of the year and one was put in service in April. These sets are to connect the 25- and 60-cycle systems of the Niagara Lockport and Ontario Power Company and are the largest sets of this kind yet built. The set is rated 25,000 kv-a., 20,000 kw. on the synchronous machine end and the induction motor which is rated 28,000 hp., 95 per cent leading power factor has the the largest rating of any induction motor in operation.

### SYNCHRONOUS CONVERTERS

Fig. 31 shows the commutator end of one of the two 4200-kw., 25-cycle lighting type converters for Edison three-wire service that were built on a certain order. The voltage range is 240 to 300, obtained by combination of transformer tap changing and field control. The base is structural steel.

Fig. 32 shows the collector end of a converter of the same rating, 4200 kw. The construction shown is typical of the present practise of one manufacturer. It utilizes a bent steel slab magnet frame, steel lugs welded on the sides to bolt the two halves together, and plate feet electrically welded to the lower half. The roller bearings are the first application made by this company of such bearings to a large converter. The pedestal supporting the bearing is made entirely of plates, cut and bent to shape, and electric welded.

There were built during the year, four twelve-phase, 4200-kw., 270-volt converters which are probably the largest twelve-phase converters in service in this country or abroad. The transformers were split into two sections, half being mounted on either side and connected to the brush-holder studs by copper bars, thus making a compact installation.

Also there were built four 5800-kw., 580-volt, 25-cycle converters for electrolytic work, the largest 25-cycle converters yet made for such service.

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## INDUCTION MOTORS

The year 1927 resembled 1926 in the absence of spectacular or revolutionary achievements which specifically could be associated with the year in question. Satisfactory progress seems to depend more and more upon careful improvement of details in design, manufacture, and application. More complete and accurate knowledge of problems in lubrication, ventilation, balance and vibration, noise, and magnetic characteristics of materials, finally results in smaller, cheaper, and more satisfactory motors. Few really novel principles may be introduced into practical applications, but the principles already available are being more appropriately employed.

### QUIET MOTORS

Increased use of motors within office buildings, hotels, theaters, etc., has involved a demand for more rigorous standards of quiet operation. These standards are being met by more careful attention to several factors of design, especially of the magnetic circuit.

In addition to the improvements thus obtained in the reduction of magnetic noise, steps also have been taken with satisfactory results to reduce noise due to windage. In the case of some 2000-hp., 1800-rev. per min. blower motors for the Boston Edison Electric Light and Power Co., in which very quiet operation was desired, the result was secured by furnishing mufflers in the air outlet of the motors.

### TOTALLY ENCLOSED MOTORS

Lines of enclosed fan-cooled motors recently have been brought out which embody improved methods of circulating the air within the motor frame. These motors are much smaller and more economical than previous types, and so have extended the possibilities of applying motors in wet and dusty situations. The improvements in this type of motor represent a more exact knowledge of the process of removing and dissipating the unavoidable losses of the motors and the reduction of these losses wherever possible. (Fig. 33.)

FIG. 33—ENCLOSED VENTILATED BALL BEARING INDUCTION MOTOR.

### LOW STARTING CURRENT MOTORS

The increasing demand for high-impedance motors with adequate starting and pull-out torque has been met by careful studies of the principles introduced many years ago by Boucherot and others. It is only in recent years that a successful compromise between the inherent limitations of this principle and the current requirements of industrial applications has been reached. In 1927 the field thus covered has been extended still further, and several manufacturers now offer extensive lines of motors of this type. One manufacturer has brought out a new motor having movable steel bars in the rotor slots, which give high reactance at starting, but which are thrown out by centrifugal force as the motor accelerates, thus securing lower reactance in normal operation.

### FREQUENCY CONVERTERS

Frequency changers of the synchronous-synchronous type have been covered under the synchronous machines.

There are two other types of frequency changers, both of which use induction motors.

The synchronous-induction type uses a synchronous motor in concatenation with an induction motor, and provides a voltage tie as well as a frequency tie between the two systems. Several of these sets have been installed in Brooklyn and two more are in process of erection. The synchronous motor is 10 poles and the induction motor is 14 poles and rated 42,000 kv-a., 300 rev. per min., 13,800 volts stator and 2700 volts rotor. (See Fig. 35.)

FIG. 34—15,000-KW. SYNCHRONOUS INDUCTION FREQUENCY CHANGER, 25/60 CYCLES

Another of this type of 15,000 kv-a. has been installed by the Potomac Electric Light & Power Co. Tests show 94.5 per cent efficiency at full load. (See Fig. 34.)

FIG. 35—35,000-KW. SYNCHRONOUS INDUCTION FREQUENCY CHANGER DURING ASSEMBLY AS SEEN FROM THE INDUCTION MOTOR END

The adjustable ratio frequency changer uses an induction motor as the driving member and some means of speed control to adjust the speed to suit a change in frequency. Their advantages are that it is possible to use sets of smaller capacity than if they were of the synchronous-synchronous type. The amount of power and its direction can be controlled at the set by settings of the relays which control its action. It is much easier to synchronize due to the adjustable speed control on the induction motor. These advantages are offset by increased cost, a little less efficiency, and added complications to the control.

In several cases, however, they have been chosen as the correct type, as at New Haven and Long Island R. R. in railway service and in several points on the Niagara Power 25-cycle lines where other 60-cycle systems desire power. The 25-cycle system is not so constant as desired by the 60-cycle systems and the adjustable ratio set allows the 25-cycle circuit to vary and still have constant 60 cycles on the synchronous machine.

Four of these sets, rated 5000 kw., were installed last year and are used to convert power from polyphase to single phase for railway service in the New York district. One of the sets for tying together power systems is now running at the Niagara Lockport & Ontario Power Co. These sets are the largest of this type, each consisting of a 25,000-kv-a., 2000-kw., 60-cycle synchronous machine and a 28,000-hp., 25-cycle induction motor, both at 12,000 volts. They tie in the 25- and 60-cycle systems and run at 300 rev. per min. The synchronous motors have 24 poles and the induction motors 10 poles. These sets deliver a constant 60 cycles on the synchronous machine when the 25-cycle system varies between the limits of 2 per cent below and 1 per cent above normal. The auxiliary commutator machines are direct-connected to the main shaft, and are excited on their rotor winding through collector rings. (Fig. 36.)

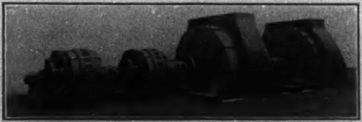

FIG. 36—SHOP VIEW OF 20,000-KW. ADJUSTABLE RATIO FREQUENCY CHANGER SET, 25/60 CYCLES

### HIGH-SPEED MOTORS

An increasing tendency to the use of high-speed motors for driving centrifugal pumps and air compressors was the practise in 1927. A relatively large proportion of these are being used for oil pipe line pumping, motors of as much as 250 hp. at 3600 rev. per min. being used for this purpose.

### SHIP PROPULSION

Although synchronous motors have been found preferable in some types of ship-propulsion equipment, the cases in which induction motors are still required are more numerous than was anticipated at the time the synchronous motor drive was introduced.

During the year, the second electrically-equipped self-unloading ore-carrier for the Great Lakes was completed and put in service, after satisfactory trial trips. This vessel had induction type main propulsion motors, and is the largest and most powerful ore-carrier on the Great Lakes. Induction motor drive is required on account of the exacting standards of flexibility in maneuvering imposed by the conditions of operation. Toward the end of the year the two airplane carriers *U. S. S. Saratoga* and *U. S. S. Lexington* were placed in commission and have been operated on their own power, although not as yet to full capacity. These induction-motor equipments were designed several years ago, and during the protracted period of ship construction have attracted attention on account of the great concentration of power involved.

Each of the 8 motors in each ship is rated at 22,500 hp. at 320 rev. per min., providing 180,000 for the ship. The size of these induction motors in hp. rating has been exceeded only recently by the induction motor on the adjustable ratio frequency changer sets mentioned above.

### STANDARDS

Agreements between the different manufacturers on standard shaft diameters and other dimensions have resulted in a recent general revision of general purpose induction motor designs. General advantage has been taken of this change to improve the design of bearings by the provision of larger oil wells and better methods of preventing oil leaks.

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## D-C. MACHINES

The developments in d-c. machines have been in the increase of limits and reliability rather than in any startling discoveries. The commutation of extra large currents has been accomplished; speeds have been increased; and the mechanical design has been simplified.

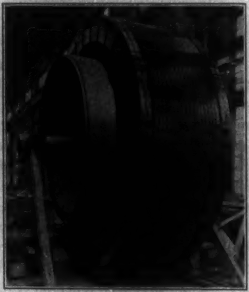

FIG. 37—ARMATURE FOR 7000-HP. REVERSING MOTOR SHOWING INVOLUTE EQUALIZER CONNECTIONS USED IN PLACE OF COMMUTATOR NECKS

*Commutation.* To improve commutation and decrease losses, especially in large units, involute equalizer connections were placed between the commutator and the armature winding in place of straight commutator necks. Fig. 37 shows these equalizers on a 7000-hp. reversing mill motor.

It has also been found that wave windings are successful in larger ratings than can be built with lap windings. This wave winding insures equal distribution of current in the armature circuit without the use of equalizers by virtue of the unusual mechanical distribution of the winding. Eleven 13,000-ampere synchronous booster converters and two 14,000-ampere field-control converters have been built with this winding and have shown improved commutating performance and reduced losses from the absence of equalizer currents.

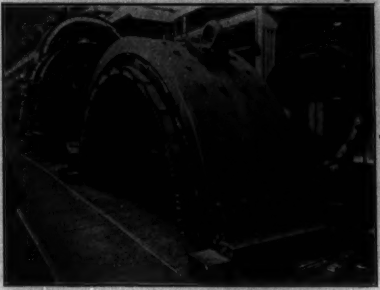

FIG. 38—A MAGNET FRAME MADE OF BENT SLABS WITH FLANGES FOR BOLTING HALVES TOGETHER WELDED ON

*High-Speed Motors.* Special requirements have led to the design of high-speed d-c. motors and results have been secured which would not have been thought possible even a few years ago. For example, during the last year, the Navy Department completed official tests on a special motor, the rating of which is 200 hp., 5000 rev. per min. This motor is used for driving a three-phase blower type compressor having a capacity of 3200 cu. ft. and a discharge pressure of 10 lb. New methods of design and construction had to be developed in order to build such a motor successfully. The peripheral speed of the armature is approximately 20,000 ft. per min. and the method of balancing was of the utmost importance. With the aid of a vibrometer, the rotor was balanced while rotating in its own bearings at the 5000 rev. per min. The bearings are flood-lubricated, oil being supplied by a separate motor-driven pump. The system of ventilation is simple and effective. The cooling air is actuated by the compressor and is drawn through the motor into the first phase of the compressor. The commutation was such that at the end of a 12-hr. duration test, the commutator surface did not show any sign of being burned or pitted.

*Welded Construction.* While welded frame motors have been on the market for a great many years, the use of this construction became much more general during 1927. In many cases, such parts as magnet frames, bases, spiders, and brush rigging are now being fabricated. Fig. 38 shows a magnet frame made of bent slabs to which flanges for bolting the halves together and supporting feet are electrically welded. Armature spiders have been built up of plate and bar material welded together on a steel hub for a large machine as shown in Fig. 39, and have been combined directly with the shaft for smaller machines, such as elevator motors shown in Fig. 40. The elevator motor shown in Fig. 40 is of further interest in that every part is of fabricated material without castings, except the rope sheave. The base is representative of such built-up parts as a substitute for castings. During 1927, the use of welded bases for all motors, generators, and motor-generator sets was extended rapidly.

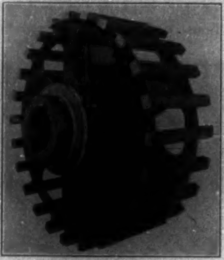

FIG. 39—ARMATURE SPIDER FABRICATED BY WELDING

FIG. 40—ELEVATOR MOTOR IN WHICH EVERY PART IS WELDED EXCEPT THE ROPE SHEAVE

*Adjustable-Speed Motors.* The principal development in adjustable-speed motors is to extend the speed range secured by field control beyond the conventional four-to-one range. Ranges of five-to-one and six-to-one have been secured. To secure successful operation at these higher-speed ranges requires very careful design and very accurate test adjustments. These higher-speed ranges have been particularly valuable in connection with application to reversing planers.

*Marine.* Motors for marine applications require special precautions against corrosion of the mechanical parts and against moisture in the windings. Although they must be installed in very cramped conditions, it is desirable to make major repairs without removing the motor from its position. If parts are not accessible, inspections will not be thorough. When failures occur, repairs must be made in the shortest possible time and often under extremely difficult conditions. Again, the application of motors aboard vessels may be taken as an example of the extreme length to which it is some times necessary to go in attaining accessibility. The case of propelling motors for submarines may be cited. The susceptibility of the lower field windings to failure has made it necessary to have some ready means of locating the defective coil and to arrange for its replacement without having to tear the ship apart. Test leads are brought out from the individual coils to a test terminal board and the whole magnet yoke is so arranged that it may be revolved in its housing and so make possible the repair or replacement of a defective field coil.

*Standardization.* For general purpose d-c. motors and generators, all manufacturing companies are now accepting such standardized dimensions as have been established by the National Electrical Manufacturers Association, with very considerable advantage, principally to the user, but also to the manufacturer. It is expected that during 1928 and 1929 still further progress will be made in this direction.

### OUTSTANDING INSTALLATIONS OR MACHINES IN PROCESS OF MANUFACTURE

*Marine.* Keeping pace with recent developments, Diesel electric drive is used to power *old type* Shipping Board vessels which, with changes in the hulls, will enable them to have greater speed, greater economy, and increased cargo capacity. Each of these ships will use a double armature d-c. motor, direct-connected to the propellor and developing 4000 s. hp. at 2 × 750 volts. The motors have been designed so that the most efficient propellor design and speed can be used, which in this case is 60 rev. per min. These will be the largest marine motors of this type in the world.

*Steel Mills.* The heaviest powered tandem hot-strip mill in the country is driven by 6 d-c. motors, each rated 2500 hp., 160/320 rev. per min., 600 volts. Power is supplied from 3 three-unit M. G. sets, each rated 3000 kw.

The heaviest powered hot-strip mill in the country requires 21,811 hp. for the main roll drive, which includes both a-c. and d-c. motors. The three a-c. motors on the roughing stands are mechanically interchangeable, although their ratings and speeds are different. The three intermediate stands are driven by three 2000-hp., 300/500-rev. per min. d-c. motors.

The four finishing stands are driven by four 3000-hp., 180/360-rev. per min. d-c. motors. The main roll d-c. motors are supplied from three 4000-kw. three-unit synchronous M. G. sets. Auxiliary motors and excitation for main drives are supplied from separate M. G. sets.

For replacing a steam engine on a reversing mill in the Chicago district, a 6500-hp. d-c. single-unit 0/60/140-rev. per min. motor will be used. This is being installed on the opposite side of the mill to reduce the shut-down period of the mill during the changeover. Welded construction is used in the bedplate for this motor and also for the flywheel M. G. set which supplies power to it.

A novel feature in a rod mill drive is the use of synchronous motor drive for all the stands except the finishing stand, which is direct current. Power is obtained from an M. G. set which at the same time drives some of the stands. The five synchronous motors have a capacity of 9600 hp. and the d-c. motor is rated 1200 hp.

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### MERCURY ARC RECTIFIERS

At the close of 1927, there were in use in the United States and Canada 53 installations of mercury arc rectifiers having a total capacity of 44,450 kw., which may be compared with the 700,000 kw. installed in the entire world. As the first of the American rectifiers was purchased in 1923, fairly rapid progress in the adoption of the mercury arc rectifier for power conversion purposes is indicated. In the tabular appendix

TABLE I
MERCURY ARC RECTIFIERS IN RAILWAY INSTALLATIONS

| | No. of sets | Tanks per set | A-c. Cycles | A-c. Volts | D-c. voltage | Kw. per set | Total kw. | Control |
|---|---|---|---|---|---|---|---|---|
| Calumet Gas and Electric Co. (Gary Street Railway) | 1 | 1 | 60 | 33,000 | 600 | 500 | 500 | Auto |
| Chicago, No. Shore & Milwaukee | 1 | 2 | | | 600 | 1000 | 1000 | Auto |
| Columbus Ry., Power & Light Co | 1 | 2 | 60 | 13,200 | 600 | 1000 | 1000 | Man. |
| Commonwealth Edison Co., Chicago | | | | | | | | |
| Lawndale | 1 | 2 | 60 | 12,000 | 620 | 1200 | 1200 | Man. |
| Whipple | 1 | 1 | 60 | 12,000 | 620 | 600 | 600 | Man. |
| Laflin | 1 | 2 | 60 | 12,000 | 1500 | 1500 | 1500 | Man. |
| Front | 1 | 2 | 60 | 12,000 | 1500 | 3000 | 3000 | Man. |
| I. C. R. R. Co., Brookdale | 1 | 2 | | 12,000 | 1500 | 3000 | 3000 | |
| Connecticut Company | 5 | 1 | 25 | 13,900 | | | | |
| | | | 60 | | 600 | 1200 | 6000 | Man. |
| | 2 | 1 | 25 | | | | | |
| | | | 60 | 13,900 | 600 | 1200 | 2400 | Auto |
| Delaware, Lackawanna & Western R. R | 1 | 1 | 60 | 4,150 | 600 | 200 | 200 | Semi |
| Lethbridge (City of) | 1 | 1 | 60 | 2,200 | 550 | 400 | 400 | Man. |
| Long Island R. R. | 1 | 1 | 25 | 11,000 | 650 | 1000 | 1000 | Semi |
| Long Island Hempstead | 3 | | 25 | | 650 | 1000 | 3000 | |
| Los Angeles Railway | 2 | 1 | | | 600 | 500 | 1000 | Auto |
| Milwaukee Elec. Ry. & Lt. Co | 3 | 1 | 60 | 26,400 | 600 | 550 | 1650 | Auto |
| Montreal Tramways | 2 | 2 | 62½ | 12,600 | 600 | 1200 | 2400 | |
| | 1 | 2 | | | | 1200 | 1200 | |
| | 1 | 2 | | | | 2400 | 2400 | Auto |
| Northern Indiana Pub. Serv. Co | 1 | 2 | | | 1500 | 1500 | 1500 | Auto |
| (Chicago, So. Shore & So. Bend Ry.) | 3 | 1 | | | 1500 | 750 | 2250 | Auto |
| North Shore Power | 1 | 1 | 60 | 2,400 | 600 | 600 | 600 | Man. |
| Philadelphia Rapid Transit | 2 | 1 | | | 600 | 500 | 1000 | Auto |
| Portland Elec. Power Co | 1 | 2 | | | 1400 | 1500 | 1500 | .... |
| Pub. Service Co. of Northern Ill. (Illinois Central R. R. Co.) | | | | | | | | |
| Volmer | 1 | 2 | | 33,000 | 1500 | 1500 | 1500 | Man. |
| United Traction | 1 | 1 | | | 600 | 500 | 500 | Man. |
| Utilities Power & Light Co. | | | | | | | | |
| (Dubuque Elec. Co.) | 1 | 1 | 60 | 13,800 | 600 | 900 | 900 | Man. |
| (Eastern N. J. Power Co.) | 1 | 1 | 60 | 2,300 | 600 | 550 | 550 | Man. |
| American Gas & Electric | 1 | 1 | 60 | 13,800 | 575 | 300 | 300 | Auto |
| City of Calgary | 1 | 1 | 60 | 12,000 | 575 | 600 | 600 | Semi Auto |
| Dominion Power & Trans. Co | 1 | 1 | 66⅔ | 13,200 | 600 | 600 | 600 | Auto |
| Canadian National Railways | 1 | 1 | 60 | 4,160 | 600 | 1200 | 1200 | Auto |
| Duquesne Light Co | 1 | 2 | | | 600 | 1000 | 1000 | Man. |
| Total | 50 | | | | | | 47,450 | |
| LIGHTING AND POWER | | | | | | | | |
| Ford Motor Company Power & Lt | 1 | 2 | 50 | 13,200 | 250 | 550 | 550 | Man. |
| Industrial | 2 | 2 | 60 | 13,200 | 460 | 1000 | 2000 | |
| New York Edison Company | 1 | 2 | 25 | 11,000 | 260 | 570 | 570 | .... |
| Henry Morgan Department Store, Montreal | 2 | 2 | | | 265 | 132 | 264 | |
| Total | 6 | | | | | | 3,384 | |

to this report, details of these installations, including frequency, voltage, and character of service of these 53 installations are given.

Reference to this appendix shows that most of the rectifier installations in this country have been made on railway systems, the few rectifier installations for Edison systems and industrial use amounting to less than 3500 kw. or 7 per cent.

Of the railway terminal electrification voltage class (1500-volt), 12,750 kw. capacity or 25 per cent has been installed, the remainder of the railway installations being of the 600-volt class and amounting to approximately 68 per cent. No installation of rectifiers for main line electrification purposes has yet been made.

In a few railway installations, dependence has been placed entirely upon rectifiers; but in most instances, rectifiers have been reinforced by converters previously installed in the same or adjacent substation.

Fig. 41—Five 1200-Kw. Mercury Arc Rectifiers at Bridgeport, Conn.

The outstanding installation during 1927 was that of the Connecticut Company at Bridgeport, Conn., which includes five 1200-kw., 600-volt units, without other converting capacity. In another substation at Stratford, the same company installed two units of the same size with complete automatic control. Fig. 41 shows these five 1200-kw. rectifiers at Bridgeport.

Another large installation of three entirely automatically-controlled 1000-kw. 650-volt units was made in the Hempstead Station to supply the Long Island Railroad.

* * * * *

Operating experience of various companies indicates that rectifiers lend themselves generally to any of the usual methods of control, the 1927 trend toward automatic control having been noteworthy.

Parallel operation of rectifiers and converters has not introduced serious difficulties, although a satisfactory method of the control of regulating characteristics of the rectifier has not been introduced.

Although current capacities and efficiencies which would warrant the use of a rectifier on the three-wire Edison system have not yet been attained, the obvious advantages of the rectifier, including its adaptability to various voltages and frequencies and the hopeful laboratory development of the manufacturers, give promise of rectifiers suitable for this service.

Limitation of current capacity has been the greatest retardant to the further extended use of the mercury arc rectifier in this country. In the development of regulating devices it seems desirable that some method other than the transformer ratio adjustment or the use of the induction regulator should be preferred.

Continuity of service is adversely affected to the greatest extent by internal short circuits within the tank. It is also adversely affected by impaired insulation within the tank and by the liberation of gas from the anode. Service restoration following interruptions which do not involve impairment of the vacuum is a simpler procedure than with synchronous apparatus, but when the vacuum is impaired the period of outages may be greater than with the flashover of a synchronous converter. Operating experience generally indicates the need of development of rectifiers along lines which will enable more rapid repairs when required within the tank. Elimination of the internal short circuit, which will dispose of this disadvantage, is hoped for, although it may be well to add that internal short circuits are usually not accompanied by impairment of the vacuum, and the rectifier may be put back into service immediately after an internal short circuit without any trouble.

Interference between rectifier and telephone circuits caused by the "ripple" in the rectified current depends largely upon the exposure between the circuits. Where the exposure cannot be reduced, band filters have been successfully used in the d-c. leads of the rectifier.

The advantages of the rectifier in voltages of 600 and above with respect to the converter for installation under limiting conditions of ventilation and permissible attendant noise are fully set forth in the manufacturers' statement which follows:

### MANUFACTURERS' STATEMENT

*Economic Advantages of Rectifiers over Synchronous Apparatus:*

Greatly reduced foundation.
Fractional weight.
Decreased transportation difficulties.
Simpler erection.
Simpler operation.
Lower operating costs.
Noiseless and vibrationless operation.
Adaptability to automatic and remote control.
Absence of synchronizing requirements.
Instantaneous starting and stopping.
Easier replacement of parts.
Increase of efficiency with voltage.
Higher efficiency over whole load range.
Independence of frequency.
Adaptability to high or low d-c. voltages.
High momentary overload capacity.
Possibility of cooling entirely by circulating water.

Some troubles experienced in the past with rectifiers were caused by corrosions, backfires, failure of the automatic vacuum valve, and telephone interferences. Today we have the necessary means at hand to overcome all these troubles. The effect of corrosion can be reduced to a negligible value by using long rubber hose connections at the cooling water intake, and a yearly overhauling and painting of the rectifier water chambers, or by using a forced draft cooling system insulated entirely from ground. In the matter of telephone interference there may be cases which would be difficult to correct and might involve expenditures of considerable magnitude. Backfires have been practically prevented by special screens inserted in the arc stream. An improved automatic vacuum valve is available and is entirely reliable. Telephone interferences wherever experienced have been very successfully eliminated by installing a special filter equipment.

The mercury seal has proved exceptionally reliable and has made possible tanks of 8 to 10 ft. in diameter. Also there has been developed by one manufacturer a unique seal consisting of a fused joint between porcelain and metal. Bushings may be removed and replaced without injury to the seal. A comprehensive system of automatically operating auxiliaries, including evacuating equipment, has been developed and a scheme of transformer connections giving the maximum utilization of transforming material without the balance coil gives promise of successful service.

The auxiliary equipment of one make of rectifiers has been considerably simplified. Anode and tank heaters and M. G. set for ignition have been abandoned. The excitation and ignition transformer, the choke coil, and the various insulation transformers are all mounted now in a common transformer tank. The auxiliaries consist of the following parts only: low- and high-stage vacuum pump; excitation and ignition; relay and transformer.

*European Developments.* In Europe the rectifier is in a great measure responsible for the steady increase of the d-c. voltages on railway systems. Already 800, 1200, and even 1500 volts are commonly used on urban, suburban, and interurban lines, with a few at 2400 and 3000 volts.

A typical example of a main railroad electrification is the 1500-volt Amsterdam-Rotterdam line of the Dutch Railways, which receives all the power from 20 Brown Boveri rectifier sets. There are several large industrial plants in Europe which depend entirely upon rectifiers as their power supply.

The most remarkable rectifier installation at the present time is the one of the Berlin Rapid Transit Company. Its system is the largest one exclusively supplied by rectifiers with a substation located at almost every passenger station.

This secures the advantage of having the power converting equipment just where the load demand is maximum, and of reducing the d-c. transmission lines and losses to a minimum. Moreover, the stray currents are greatly diminished, and consequently their destructive effect is also reduced. The interferences between d-c. lines, telephone and signal lines due to the pulsation in the rectified current are therefore practically eliminated. Altogether, the feeding of the "city" and "outer circle" railway lines require 34 substations with a total of 98 rectifier units, amounting to a total of installed capacity of 117,600 kw. The suburban lines branching out from the urban and outer circle lines are fed by 9 substations, each equipped with three or four units. Their total aggregate capacity is 36,000 kw. The primary supply for all these rectifier substations is 30,000-volt, three-phase, 50-cycle. The d-c. voltage is 800 volts.

The initial substation equipment is being supplied by Brown Boveri for this system and comprises for the initial development:

92 Rectifier cylinders, rated for a continuous output of 1200 kw. at 800 volts, with vacuum pumps and auxiliaries.

90 Rectifier transformers O. I. S. C.

90 Absorption reactance coils.

136-2000-ampere high-speed circuit breakers.

Other complete units are being supplied by other companies as follows:

10—Siemens Schuckert Works
10—Allgemein Elect. Co.
10—Bergmann Co.

The decision of the German Railways Company to use mercury arc rectifiers exclusively for the electrification of the important Rapid Transit Railways system of Berlin is of utmost importance for the future development of this type of converting apparatus, and shows clearly the confidence the engineers have in this equipment. The electrification of the Berlin Rapid Transit system will be no doubt the largest and most up-to-date rectifier installation in the world.

*Performance Standards.* Owing to the comparatively recent introduction of the mercury arc rectifier into this country the formulation of performance standards has not been undertaken to date. Definite procedure towards this end is, however, now under way. Performance guarantees of European practise will be studied and steps taken to put the matter of performance standards on a logical basis without hampering development.

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# Transmission and Distribution

## ANNUAL REPORT OF THE COMMITTEE ON POWER TRANSMISSION AND DISTRIBUTION*

*To the Board of Directors:*

In addition to conducting its usual activities this committee has during the current year endeavored to establish a closer contact with those committees of other organizations whose interests lie in a large measure within the field with which it is concerned. It was felt that such cooperation would be mutually beneficial and would result in the presentation through the medium of the Institute publications of some material of general interest which would otherwise receive only limited circulation. It is believed that the present report has benefited very materially by this policy.

After considering some criticisms of the definitions contained in the "Wires and Cables" section of the A. I. E. E. Standards the committee deemed it advisable to have these definitions revised. A suggested revision has been prepared and placed in the hands of the Standards Committee.

The committee has been fortunate in securing several interesting and timely papers for presentation and publication by the Institute, some of which have not yet appeared. References to these papers will be noted under the appropriate headings in the following text.

### OVERHEAD TRANSMISSION LINES

*Lightning on Transmission Lines.* The protection of overhead transmission lines from interruptions due to lightning flashovers remains a problem of outstanding importance and in order to make more quickly available records of operating data on the protective value of ground wires, fused grading shields, and wood or combination steel and wood transmission line structures with regard to reducing lightning flashovers, a subcommittee undertook to collect as much information in this field as possible. A certain amount of information has been obtained and is presented herein, but more complete data are being sought and it is hoped to be able to present at an early date the inferences to be derived therefrom.

Table I gives data submitted by seven companies. Since no means avail to make direct comparisons of thunderstorm severity, it is obvious that while inferences may be made, conclusions cannot be drawn from these data.

Better performance resulting from adding a ground wire to an all-wood line seems clearly indicated from the comparison of 1926 and 1927 experience with that of 1925 of the data reported by companies No. 1 and No. 5. Similar improvements in reliability are indicated when ground wires have been added to steel tower lines.

On the other hand the data on the wood pole lines without ground wires, reported by companies No. 5 and No. 6, indicate in general less outages than the data on steel lines with ground wire, reported by others, indicating the apparent value of the wood as insulation in reducing flashovers.

Western companies report bird troubles as being more severe than those due to lightning, and wood construction very advantageous in this respect as shown by the data submitted by Company No. 6. However, there seems to be a crystallization of sentiment in the West in favor of steel towers with suitable bird guards, because of the very considerable trouble experienced with destructive fires due to leakage currents with wood construction, especially at certain seasons of the year.

Further light on the protective value of the ground wire is indicated by a comparison of the relative flashovers between 13 lines without ground wires totaling 412 mi. and four lines with ground wires totaling 229 mi.

Both groups are associated with the same systems, the lines being located in four different Middle West states.

There were in 1925, 36 interruptions for lines without ground wires, as against 2.2 interruptions for lines with ground wires, per 100 mi. of circuit.

Records for twelve consecutive years on a 110-kv. double-circuit line some 140 mi. long with single ground wire show an average of less than four interruptions per year per 100 mi. from lightning, and such interruptions constituted but one-third of the outages from all causes in that period. This line is subjected to as many as 70 to 80 electrical storms each year.

It may be noted that Company No. 8 had 36 and 28 breaker openings per 100 mi. in 1926 and 1927 respectively, although a ground wire was in service. Although this number seems large there may be satisfactory explanations which would become apparent if the somewhat insufficient data were more complete.

For lower voltage lines, 22 to 66 kv., there is an increasing tendency to try to improve designs of wood

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*POWER TRANSMISSION AND DISTRIBUTION:

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*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

TABLE I

| Company No. 1 | 50 ft. wood poles & wood arms | | |
|---|---|---|---|
| | 1925 | 1926 | 1927 |
| No. of storms | 58 | 57 | 50 |
| Breaker openings due thereto | 56 | 20 | 28 |
| Insulator replacements due thereto | 25 | 8 | 7 |
| Miles of circuit—66 kv | 71.2 | 71.2 | 71.2 |
| Breaker openings per 100 mi | 78.8 | 28.1 | 39.4 |
| Insulator replacements—per 100 mi | 35.2 | 11.25 | 9.85 |
| Ground wire | No | Yes | Yes |

| Company No. 1 | Steel tower lines | | |
|---|---|---|---|
| | 1925 | 1926 | 1927 |
| No. of storms | 57 | 50 | 50 |
| Breaker openings due thereto | 7 | 6 | 3 |
| Insulator replacements due thereto | 9 | 10 | 1 |
| Miles of circuit—66 kv | 96 | 48 | 48 |
| Breaker openings per 100 mi | 7.3 | 12.5 | 6.25 |
| Insulator replacements—per 100 mi | 9.4 | 20.8 | 2.08 |
| Ground wire | Yes | Yes | Yes |
| Fused grading shields | No | No | Yes |

| Company No. 4 | Steel tower lines | | |
|---|---|---|---|
| | 1925 | 1926 | 1927 |
| No. of storms | 65 | 67 | 70 |
| Breaker openings due thereto | 32 | 27 | 37 |
| Insulator replacements due thereto | 45 | 10 | 115 |
| Miles of circuit—132 kv | 140 | 372 | 401 |
| Breaker openings per 100 mi | 23 | 7.25 | 9.25 |
| Insulator replacements—per 100 mi | 32.3 | 2.70 | 28.7 |
| Ground wire | No | Yes, partially | Yes |

In 1926, 50 mi. were unprotected all year, and 256 mi. were unprotected by ground wire until after June 1st; fourteen storms were recorded prior to June 1st.

In 1927, 50 mi. were still unprotected by ground wire until after October 1st; sixty-four storms were recorded prior to October 1st.

| Company No. 5 | Wood pole lines | | |
|---|---|---|---|
| | 1925 | 1926 | 1927 |
| No. of storms | 2 | 2 | 3 |
| Breaker openings due thereto | 0 | 0 | 0 |
| Insulator replacements due thereto | 0 | 0 | 0 |
| Miles of circuit—110 kv | 29.1 | 29.1 | 29.1 |
| Ground wire | Yes | Yes | Yes |
| Average height of ground wire | 48 ft. | 48 ft. | 48 ft. |

| Company No. 5 | Wood pole lines | | |
|---|---|---|---|
| | 1925 | 1926 | 1927 |
| Number of storms | | 5 | 12 |
| Breaker openings due thereto | | 1 | 3 |
| Insulator replacements due thereto | | 0 | 3 |
| Miles of line—110 kv | 0 | 120 | 237 |
| Breaker openings per 100 mi | | .83 | 1.27 |
| Insulator replacements per 100 mi | | 0 | 1.27 |
| Ground wire | | No | No |

| Company No. 5 | Wood pole lines | | |
|---|---|---|---|
| | 1925 | 1926 | 1927 |
| Number of storms | 5 | 7 | 18 |
| Breaker openings due thereto | 0 | 3 | 7 |
| Insulator replacements due thereto | 0 | 3 | 3 |
| Miles of circuit—55 kv | 614 | 494 | 672 |
| Breaker openings per 100 mi | 0 | .61 | 1.04 |
| Insulator replacements—per 100 mi | 0 | .61 | .45 |
| Ground wire | No | No | No |

| Company No. 6 | Wood line 1927 | Steel line 1927 |
|---|---|---|
| Miles of line—110 kv | 41.7 | 42.8 |
| Flashover from lightning | 1 | 4 |
| Flashover from birds | 0 | 11 |
| Flashover from insulator failure | 0 | 1 |
| Ground wire | No | No |

These lines are installed between the same substations.

| Company No. 8 | Steel tower line | | |
|---|---|---|---|
| | 1925 | 1926 | 1927 |
| Number of storms | No record available. | | |
| Breaker openings | 1 | 9 | 7 |
| Miles of circuit—154 kv | 25 | 25 | 25 |
| Breaker openings per 100 mi | 4 | 36 | 28 |
| Ground wire | Yes | Yes | Yes |
| Height top line conductor | 65 ft. | 65 ft. | 65 ft. |

| Company No. 9 | Steel tower line | | |
|---|---|---|---|
| | 1925 | 1926 | 1927 |
| Number of storms | No record available | | |
| Breaker openings | 1 | 1 | 0 |
| Miles of circuit—110 kv | 104 | 104 | 104 |
| Breaker openings per 100 mi | 0.96 | 0.96 | 0 |
| Ground wire | Yes | Yes | Yes |
| Height top line conductor | 65 ft. | 65 ft. | 65 ft. |

| Company No. 12 | Steel tower line | | |
|---|---|---|---|
| | 1925 | 1926 | 1927 |
| Number of storms | 37 | 39 | 31 |
| Breaker openings due thereto | 19 | 34 | 8 |
| Insulator replacements due thereto | 33 | 82 | 8 |
| Miles of circuit—120 kv | 41 | 81 | 120 |
| Breaker openings per 100 mi | 46.4 | 42 | 6.7 |
| Insulator replacements per 100 mi | 80.6 | 101 | 6.7 |
| Ground wire | No | No | Yes |

pole lines with a view to reducing lightning troubles by the use of wood pins, arms and braces, and by increasing the amount of insulation inserted in the guy wires.

Company No. 1 reporting on the value of fused grading shields shows a fifty per cent reduction in outages on two circuits, on one tower line, so equipped compared with two circuits on a parallel tower line protected by ground wire only. It also states that this type of protection functioned correctly two out of every three times, *i. e.*, cleared the follow-up dynamic arc before the breakers opened and thus avoided dumping the load. The record as to the performance of the individual fuses was even better—77 per cent correct operation, *i. e.*, 77 per cent cleared properly and were not the cause of a line interruption.

Another company desirous of trying out this type of protection on 132-kv. circuits reports that it has not as yet been able to find a fuse for that voltage which, after testing, it felt was safe to install for this purpose.

The subcommittee has also secured a contribution to the report covering some of the more theoretical phases of this subject, and this constitutes the following material having to do with the theory of lightning and ground wires being herein presented not particularly as representative of the views of the committee as a whole, but rather as being of general interest and stimulative of further thought and study on the more theoretical aspects of this subject.

*Theory of Lightning and Ground Wires.* The results of the work of a number of investigators during the past year have altered to some extent the conceptions regarding the nature of the lightning stroke and the manner in which it affects transmission lines. The fundamentals of the "breaking drop" theory of the accumulation of the cloud charge, as proposed by G. C. Simpson, is generally accepted. According to this theory, the upward air currents in the front of the cloud, blowing past the condensed vapor in that region, break up the larger drops, as they form, and leave the divided parts with a positive charge. The passing air with finely divided spray carried off the corresponding negative charge to the upward and rearward portion of the cloud. Upon the recombination of the positive drops the potential is raised, due to the decrease in total surface; and likewise, in the negative part of the cloud the potential is raised as the charge is imparted to the vapor which condenses and forms into drops. According to this conception, the first part of the storm, and that with the heavy rain, is accompanied with the positively charged part of the cloud. The latter part of the storm, and the usually finer, drizzling rain, is accompanied with the negatively charged part of the cloud. Much of the accumulated charge of the cloud is carried to earth with the falling rain but the accumulation is, in general, more rapid than the dissipation by this means. The result is the familiar lightning flash between cloud and earth or between oppositely charged portions of cloud.

An electrical discharge between oppositely charged bodies starts, of course, when the stress at one of the electrodes reaches a state where ionization by collision begins. This state requires that potential gradient which gives free electrons a speed sufficient to knock off other electrons when they collide with neutral molecules. When an electron with this speed collides with a molecule but does not succeed in knocking off another electron, a considerable amount of heat is generated. If the stress reaches the breakdown potential of 30,000 volts per cm., the concentration of free electrons becomes so great, and the collisions with molecules become so frequent that the gas is heated to the point where thermal ionization begins. This forms the start of a streamer. Along such a streamer the gradient is low, which increases the stress at the ends. This further increases the concentration of ionization at the ends and promotes the progress of the streamer. Due to the difference between the speeds of negative electrons and positive ions, the speed of growth of the streamer toward the anode is much greater than that toward the cathode. This accounts for the difference between the growth of lightning strokes from negatively and positively charged clouds. However, in either case the speed is limited. It has been shown by various tests that with practical amounts of energy the maximum speed of growth of these streamers between electrodes of various shapes is of the order of one-tenth to one-fiftieth the speed of light. The completion of this arc establishes a conducting connection between the electrodes and an electrical current is free to pass, being governed by the impedance of the entire circuit involved.

In the discharge of a cloud to earth it is incorrect to consider the charge being released as concentrated in the first streamer. The streamer merely sets up the path, and as stated above, the growth is a relatively slow process. Considering the distances and speeds involved, it must take a time of at least 10 and probably 50 microseconds to accomplish this. After the path is established the charge is free to travel to earth as a traveling wave as fast as it can gather from the cloud. The progress of this is restricted, since the charge is distributed throughout a relatively non-conducting body. It is necessary for the path to branch out and collect the charge. Beyond this retarding effect, the rate at which the charge can pass to earth is determined by the potential of the cloud and the surge impedance of the lightning path. This surge impedance is a variable since it depends upon the diameter of the path and the distance above the earth. Although it is not quantitatively known it definitely limits the intensity of the lightning flash. When the lightning strikes a transmission line directly, the traveling wave from the lightning path divides, and propagates in two directions, with two-thirds voltage, in the same manner as when an ordinary line branches into two parts.

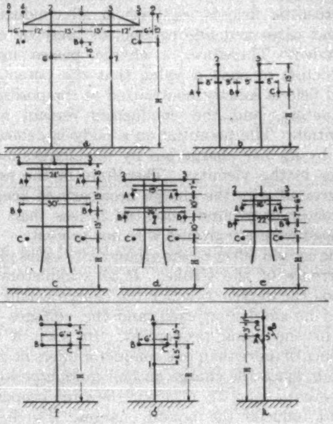

FIG. 1—TYPICAL ARRANGEMENT OF GROUND WIRES ON TRANSMISSION LINES

It is easily seen that this phenomenon limits the intensity of the surge, and many of them are probably quite weak. There is considerable reason to believe that, of the lightning surges experienced on transmission lines, a larger percentage is due to direct strokes than has generally been believed. In order for an induced surge to attain important magnitude, not only must the gradient be very intense, but the discharge must be extremely rapid. The gradient falls off rapidly from directly beneath the cloud outwards, and unless the discharge is extremely rapid the bound charge has time to distribute itself over the line.

It is now generally recognized that a great amount of protection is afforded by the use of ground wires on transmission lines. Much of the disrepute into which ground wires fell was due to poor mechanical installation and the use of non-weather-resisting material, which did not provide a life comparable to that of the rest of the line. In the installation of ground wires the same degree of weather resistance and the same quality of installation should be used as in the rest of the line so that the ground wires do not fail previous to the line conductors.

Ground wires are valuable in protecting the line both from induced and direct strokes. The manner in which the ground wire protects against induced strokes is as follows: Due to the slow rate at which the cloud electrostatic field is established, all conductors, both ground wires and line conductors, may be considered grounded. Therefore, a charge passes up on the conductors of such a value that the potential of the cloud field is exactly neutralized at the positions of the conductors, and the conductors remain at ground potential. The potential on a body is determined not only by its own charge but by the charges on all other bodies in the vicinity. Therefore, in the presence of the ground wire the charge necessary to keep the line conductor at ground potential is less than would be required were the ground wire not present.

The second effect of the ground wire takes place at the occurrence of the stroke. If all conductors were insulated the degree to which the charge would be bound would be similar on each, and the voltages would all rise in the same proportion. In such a case, the presence of more than one conductor offers no protection to each, since the charge on one conductor would raise the potentials on the others in the same proportion that it had reduced the bound charges. Furthermore, if the discharge of the cloud were instantaneous the ground wire would offer no protection, since the bound charges would then have no time to readjust themselves, and upon the disappearance of the cloud field the charges would be those which would raise the potentials of the conductors to the potentials of their positions in the cloud field before the stroke, but of opposite polarity. However, in the actual case the ground wire is grounded, and there is a certain time lag in the disappearance of the cloud field. It has been assumed that this time lag is sufficient to permit the necessary readjustment of charges on the ground wire to keep it at ground potential in the absence of the cloud field and the presence of the charge on the line conductor, the latter not being able to get away on account of the higher insulation and the rapidity of the field collapse. During the past season, klydonographs have been connected to ground wires at a number of locations, and the highest potentials recorded near a tower were of the order of 20,000 volts, which verifies the validity of the above assumption. It is obvious that, in order to remain at ground potential in the presence of the charge on the line conductor, the new charge on the ground wire must be of opposite polarity. This charge of opposite sign reduces, rather than raises, the potential on the line conductor due to its own charge. A simple way of stating the effect of ground wires in connection with induced strokes is, that it decreases the capacity of the line conductor to ground before the stroke and increases this capacity after the stroke.

Quantitatively, ground wires reduce the potentials induced on lines by lightning by from 25 to 75 per cent, depending upon the number and arrangement of the ground wires. The number of ground wires to use is of course an economic problem to be considered in relation to the amount of protection desired.

The most efficient arrangement of the ground wires is that which gives the greatest geometrical mean radius of the ground wire system and the least geometrical mean distance of this system from the conductors being protected. Table II gives the protection afforded by various numbers of ground wires on lines of various standard voltages.

The amount of protection afforded by ground wires against direct strokes is not so easily determined. However, since the ground wires are, or should be, located above the line conductors they are much more likely to receive the stroke of lightning than the conductors themselves. In view of the limitation of the intensity of the lightning stroke, as discussed above, it is easily seen that the less severe strokes might hit the ground wire and still not induce sufficient voltage on the line conductor to cause a flashover.

The protection against flashover afforded by the use of ground wires is much greater than the percentage reduction in voltages. If the number of lightning surges of any given potential is plotted against the voltages, the resulting curve resembles a rectangular hyperbola. From this it is seen that of those lightning strokes, both direct and induced, which cause flashover, those that are not more than twice the flashover voltage of the insulators are much more numerous than those which are many times that value. Therefore, if each surge is reduced to one-half its voltage, the number of flashovers is reduced by a much larger factor. Operating experience of the past few years seems to indicate that on the higher voltage lines flashovers are practically eliminated by ground wires which give a 50 per cent reduction.

*Topography in Relation to Lightning Flashovers.* An investigation of the flashovers which have occurred on the Cahokia–Crystal City transmission line, which was put in service May 11, 1925, indicated a close relationship between the topography of the surrounding territory and the flashovers on the line. This relationship was demonstrated by plotting on a topographical map the location of all the flashovers whose positions

TABLE II

THEORETICAL PROTECTIVE VALUE OF GROUND WIRES

| Line | | | Ground wires | | | Per cent reduction | | | | Induced crest voltage for a gradient of 50 kv. per ft. | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kv. | Fig. I | H* | No. | Location | Dia. in. | A | B | C | Ave. | A | B | C |
| 220 | a | 50 | 0 | | | | | | | 2500 | 2500 | 2500 |
| | a | 50 | 1 | 1 | 1/2 | 21 | 31 | 21 | 24 | 1980 | 1720 | 1980 |
| | a | 50 | 2 | 2, 3 | 1/2 | 36 | 45 | 36 | 39 | 1600 | 1370 | 1600 |
| | a | 50 | 3 | 1, 4, 5 | 1/2 | 48 | 55 | 48 | 50 | 1300 | 1120 | 1300 |
| | a | 50 | 4 | 2, 3, 6, 7 | 1/2 | 48 | 61 | 48 | 52 | 1300 | 975 | 1300 |
| | a | 50 | 5 | 1, 4, 5, 6, 7 | 1/2 | 55 | 66 | 55 | 58 | 1120 | 850 | 1120 |
| 220 | b | 27 | 0 | | | | | | | 1350 | 1350 | 1350 |
| | b | 27 | 2 | 2, 3 | 1/2 | 34 | 44 | 34 | 37 | 890 | 760 | 890 |
| 132 | c | 45 | 0 | | | | | | | 3550 | 2900 | 2250 |
| | c | 45 | 1 | 1 | 1/2 | 29 | 26 | 24 | 26 | 2530 | 2160 | 1700 |
| | c | 45 | 2 | 2, 3 | 1/2 | 45 | 39 | 37 | 40 | 1930 | 1760 | 1410 |
| | c | 45 | 2 | 4, 5 | 1/2 | 48 | 41 | 39 | 42 | 1850 | 1700 | 1370 |
| | c | 45 | 3 | 2, 3, 6 | 1/2 | 51 | 52 | 51 | 51 | 1760 | 1410 | 1110 |
| 110 | d | 40 | 0 | | | | | | | 3000 | 2500 | 2000 |
| | d | 40 | 1 | 1 | 1/2 | 30 | 26 | 25 | 27 | 2090 | 1850 | 1490 |
| | d | 40 | 2 | 2, 3 | 1/2 | 48 | 42 | 40 | 43 | 1560 | 1440 | 1190 |
| | d | 40 | 3 | 1, 2, 3 | 1/2 | 59 | 51 | 49 | 53 | 1230 | 1220 | 1020 |
| 66 | e | 35 | 0 | | | | | | | 2450 | 2100 | 1750 |
| | e | 35 | 1 | 1 | 1/2 | 31 | 28 | 26 | 28 | 1690 | 1510 | 1290 |
| | e | 35 | 2 | 2, 3 | 1/2 | 49 | 43 | 42 | 45 | 1250 | 1200 | 1010 |
| | e | 35 | 3 | 1, 2, 3 | 1/2 | 60 | 54 | 51 | 55 | 980 | 970 | 830 |
| | f | 26 | 0 | | | | | | | 1525 | 1300 | 1300 |
| | f | 26 | 1 | 1 | 3/8 | 28 | 29 | 36 | 31 | 1095 | 930 | 835 |
| | g | 26 | 0 | | | | | | | 1525 | 1300 | 1300 |
| | g | 26 | 1 | 1 | 3/8 | 15 | 22 | 22 | 19 | 1300 | 1020 | 1020 |
| 33 | h | 30 | | | | | | | | 1500 | 1575 | 1650 |
| | h | 30 | 1 | 1 | 3/8 | 38 | 40 | 46 | 42 | 930 | 945 | 890 |

H* = Height of lowest conductor.

have been reported since the line was put in service.

This line follows the low lands on the Illinois side of the Mississippi River to a point opposite Crystal City where it crosses to the high bluffs on the Missouri side. On the western side there are no high hills, except those near Crystal City. On the eastern side, steep bluffs parallel the line almost for its full length at a distance of from one to three miles. The prevailing path of the storms in this part of the country is from the directions between southwest and northwest.

The flashovers have occurred in groups with four to five miles having excessive flashovers and adjacent sections of similar length having but few. At the southern end, clouds pass over the high hills on the west side of the river and discharge to or near the line, causing a large number of flashovers. Farther north the clouds coming from the southwest do not pass over any high hills, retain their charge, pass over the bottom lands and discharge to the bluffs on the eastern side. At the time of discharge the cloud probably extends back over the line and the sudden release of the charge induced on the line by the passage of the cloud over it causes flashover. The nearer the line to the bluffs the greater the number of flashovers.

A number of flashovers along two miles of line, some three or four miles south of Cahokia, cannot, however, be accounted for on the above basis.

From this study, it appears that short sections of ground wire placed over the portions of the line most subject to flashovers should be almost as effective from the standpoint of protection as a ground wire over the entire length. Eight miles of ground wire divided into four sections would include those parts of the line upon which 70 per cent of the flashovers have occurred. The line is a double circuit one, 31 mi. in length. Two miles of ground wire have been installed over the Missouri bluffs and the other six miles will be installed as outlined above. It may well be that partial protection of this type will offer a maximum of insurance for a minimum of investment.

*Symposium on Surge Voltage Investigations.* Attention is called to the symposium on surge voltage investigations which is on the program of this convention and is being presented under the auspices of this committee (see p. 1111). Some of the papers in this group are in the nature of reports of progress of investigations which are not as yet completed and further reports will be awaited with the same interest with which the present papers will undoubtedly be received.

One paper of this symposium, entitled *Surge Voltage Investigation on the 132-Kv. Transmission Lines of the American Gas & Electric Co.*, presents the preliminary results of an extensive klydonograph layout which was planned and placed in operation during 1927 in connection with studies of the Subcommittee on Lightning. The investigation was made possible through the cooperation of the General Electric Co., the Westinghouse Electric & Manufacturing Co., and the American Gas & Electric Co.

The data secured during 1927 require further study and are too incomplete at present for many definite and final conclusions to be drawn. Switching surges were recorded up to 5.2 times normal to ground, checking quite closely previous data on this phase of the problem: All switching surges were either highly damped or unidirectional with small magnitude. These surges do not appear to be at all troublesome to line or apparatus, at least in the line investigated. Lightning voltage surges were recorded up to 4.8 times normal and in one case where the line tripped over 19 times normal was found. Of the surges recorded 57 per cent were positive, 18 per cent were negative, and 25 per cent oscillatory.

Lightning arrester discharges were found as high as 2620 amperes in the neutral leg of a four leg oxide film arrester on a 132-kv. system. Another case of 1260 amperes was observed. Both currents were negative initially, the latter being highly damped.

Voltages on the protective ground wire were observed as high as 20,000 volts in one case, and many voltages were recorded in the order of 2000 to 3000 volts.

The work, so far, indicates that surges of lightning origin having an initially high value, do not spread far on the line before rapid attenuation reduces them very materially. The waves are highly attenuated in the first five miles or so of travel.

Voltage surges due to switching were found to travel the entire length of the 73-mi. line with little apparent attenuation. There was a noticeable reflection of the voltage at the open end of the line which died out in a few miles of return travel.

On these particular lines it was found that the voltage surge on deenergizing the line was about double that which was found on energizing the line. Switching on these lines was done on the 132-kv. circuit, and not on the low side of the step-up transformers, a condition which is thought to have influenced the results. Further data are being obtained on this feature of line switching.

The field investigation is being continued in 1928 and it is expected that after the data for 1928 have been collected and assimilated a fairly complete report can be presented.

*Insulation of Transmission Lines and Connected Apparatus.* The tendency in power transmission has been to increase the insulation of some portions of the system, particularly the line, to a point at which it is fairly immune from flashover due to lightning. This tends to place a greater stress on the other apparatus and therefore requires a corresponding increase in its insulation.

The papers on *Relation between Transmission Line and Transformer Insulation*, by W. W. Lewis, (see p. 1111) and *Rationalization of Transmission-System Insulation Strength*, by Philip Sporn, (see p. 1132) which were presented at the New Haven Regional Meeting, point out the anomalous features of this situation and suggest concrete steps to be taken toward its rectification.

*Horizontal Spacing of Transmission Line Conductors.* While the horizontal spacing of conductors in a transmission line is ordinarily determined by the clearance necessary at the tower to permit the swinging inward of the insulator strings, there are, nevertheless, cases where this spacing is determined to avoid danger of contact of the conductors out in the span. Among such cases are the occasional lines with six horizontally spaced conductors on one tower (as in the case of the Davis Bridge Line of the New England Power Company) and long spans; also some wood pole lines where the poles do not carry a ground wire.

A paper by Mr. P. H. Thomas (see p. 1323), covering this subject in detail and proposing an empirical formula for the determination of the necessary spacing as depending upon the danger of contact out in the span, has been secured and is being presented at this convention.

*Transmission Line Conductor Vibration.* Investigations have been carried on through the year on the vibration of transmission line conductors of various materials in service. These records obtained in the field have been supplemented by experimental work at the Carnegie Institute of Technology in Pittsburgh.

The general results of these records and investigations are covered in a paper by Theodore Varney, (A. I. E. E. Quarterly TRANS., 1928, Part 3, p. 799), read at the St. Louis Regional Convention on March 9, 1928.

These investigations confirm the fact that resonant vibrations are due to wind of rather low velocity. The effects of these vibrations are more marked when the conductor or cable consists of a strong material giving a high elastic limit, as would be expected.

It appears that practically all wires or stranded cables suspended in the air are in a constant state of vibration. It is only, however, when the wind velocity is uniform throughout the span and bears certain definite relations to the elastic characteristics of the span that resonant vibration of considerable amplitude is set up.

Resonant vibration of considerable amplitude has been observed and recorded in many cases. In comparatively few of these cases has damage to the conductor or cable resulted. It is to safeguard such cases, however, that the investigation has been carried on and comparatively simple methods for overcoming these difficulties have now been suggested.

In view of the complexity of the problem and the consequent difficulty of prophesying in advance whether or not trouble may arise, it appears probable that some one of the several comparatively simple safeguards which have been developed should be considered in the design of any new transmission line of importance.

It is believed to be a simple and sound principle to reinforce a transmission conductor at its point of support, particularly if the spans are long, the weather conditions severe, and the line important.

*Movements of Overhead Line Conductors during Short Circuits.* A paper by W. S. Peterson and H. J. McCracken, Jr., covering a considerable amount of experimental data on the movements of overhead line conductors due to electromagnetic forces under short circuit conditions was presented at the Pacific Coast Convention in August (A. I. E. E. Quarterly TRANS., Vol. 48, No. 1, Jan. 1929). In overhead lines where heavy short circuit currents are encountered, this is a feature of design which cannot be neglected, and it is hoped that the paper mentioned, together with other available information, will make possible a more rational treatment of this problem.

### UNDERGROUND CABLES

*General Review.* The outstanding feature of underground transmission during the year is the placing in service in the summer of 1927 of 18 mi. of 132-kv. lines in Chicago and New York. These installations were described before the Institute at the Chicago Regional Meeting in November 1927. There have been no electrical failures on these installations, and the only troubles have been minor oil leaks in joints and other appurtenances and a few leaks in cable sheaths. In all cases of leaks the repair work was deferred until the line could be taken out of service without inconvenience to the operating company.

No marked developments in the design of underground cable for general use have taken place during the year. Impregnated paper insulation is very generally employed and wood pulp paper is rapidly replacing manila paper. The advantages due to the superiority of the mechanical properties of manila rope paper over wood pulp paper have very largely been overcome by reason of improvements in the production methods with wood pulp paper. On the other hand, the latter has a higher dielectric strength than the manila paper which has thus far been used and research investigations have shown it to have as high temperature limitations. Sector shape conductors are being very largely used in high voltage three-conductor cable. Shielded type three-conductor cable is being marketed by a number of manufacturers for the higher operating voltages and some manufacturers of single-conductor cable for extra high voltage three-phase operation are recommending the use of the shielded type of construction for such cable.

All of the available evidence indicates that on the whole there has been a distinct improvement in the quality of high voltage cable during the past few years. Statistics on more than 5,000,000 ft. of such cable purchased under rigid specifications by a group of central station companies show that only 3.22 per cent of the cable submitted during 1927 was below the standards prescribed by the specifications,—the lowest of continually decreasing percentages during the past five years. There has been a steady increase in dielectric strength of cable during the past few years. Dielectric losses and power factor are at about a minimum,—the average power factor for cable with a wide range of voltage ratings and sizes being about 0.6 per cent at room temperature and operating voltage.

Another outstanding feature has been the marked decrease in the effect of bending on the dielectric strength of paper-insulated lead-covered cables. For the past two or more years cable could be subjected to a very severe bending manipulation without any appreciable effect on the dielectric strength.

Existing specifications provide certain maximum allowable operating temperatures for impregnated-paper-insulated cables depending upon the rated voltages. Neither these specifications nor the standards of the A. I. E. E. specify a method of determining the maximum temperature in the cable during operation. In order to make a start on clearing up this situation the subcommittee on impregnated-paper-insulated cable research has made arrangements with the Massachusetts Institute of Technology for studies on the thermal resistivity of impregnated paper insulation, including the devising of a standard method of measuring the resistivity which will be acceptable to the manufacturers and users.

*Cooperative Activities.* A number of the central station companies that purchase large quantities of underground cable annually, cooperate in the inspection and testing of new cable, in the analysis of a large amount of inspection and test data thus made available, and in a certain amount of experimental research work. These statistical analyses are the basis of the above statements in reference to quality improvement.

Among the research studies which have been made, one on the relative dielectric strength of single-conductor versus three-conductor cable indicated that single-conductor cable has a dielectric strength which, if expressed as the average voltage gradient which will cause failure in 10 hr., is about 60 per cent greater than that of three-conductor belted type cable, the advantage over shielded three-conductor cable being about half that amount.

Manufacturers of cable, however, are in good agreement that the advantage in dielectric strength of single-conductor cable as compared to three-conductor belted cable for these conditions is only about 30 per cent, with a corresponding reduction to possibly 15 per cent for shielded three-conductor cable. Further investigation of the data will probably serve to reconcile the discrepancies between these figures.

Another rather extensive investigation has established the relationship between life and voltage for modern cable, namely, that the life varies inversely with approximately the sixth power of the voltage in the case of single-conductor cable and approximately the seventh power of the voltage in the case of three-conductor cable within the range of the test.

*Effectiveness of Specifications and Cable Performance.*

The effectiveness of specifications and the accompanying inspection and tests in guaranteeing satisfactory service of cable are often questioned and few data exist from which definite conclusions may be drawn. Obviously the answer to this question can be found only by following the history of inspected cable after it goes into service. The importance of this question and the still greater importance to the operating engineer of thoroughly reliable records of cable performance have been recognized and all of the important data in connection with all failures of cable in service on a number of the larger systems are now being systematically collected. It is believed that these studies will yield some very important results but they have not yet been continued long enough to justify conclusions. However, it has already been found that a very considerable percentage of the sections of cable which failed in service without external cause had some abnormal feature of more or less significance in the original inspection record.

*Quality Rating.* It is generally recognized that all items of inspection and test are not of equal value, and that no one characteristic determines the quality of a given piece of cable. On the other hand it is probably true that no two engineers will agree as to just which characteristics do determine cable quality. Nevertheless it is appreciated that a method of weighing characteristics, assigning grades on a scale of test performance for each characteristic and thereby obtaining a single figure of merit for a given lot of cable, would furnish an engineer with a useful means of evaluating that cable. Such a procedure of quality-rating has been set up and is now being applied in the cooperative work referred to above. Such a procedure, even though strictly empirical, will, if it proves to coordinate with service records, be of great value to the industry.

*Losses in Armored Single-Conductor Cables.* The calculation of potential drop and energy loss in single-conductor steel armored cables used for three-phase circuits is not susceptible of accurate predetermination with the information now available.

In 1909, J. B. Whitehead and H. W. Fisher (TRANS. A. I. E. E., Vol. 28, p. 737, and TRANS. A. I. E. E., Vol. 28, p. 747 respectively) published some experimental data on this subject supplemented by theoretical discussions. The Whitehead formulas are revised in the light of further discussions in Wm. A. Del Mar's *Electric Cables*, 1924, p. 142.

Since that date the subject of drop in *unarmored* single-conductor cables has been very fully discussed in series of monographs in the *Journal* of the Institution of Electrical Engineers (London 1926 and 1927) and the theoretical principles evoked seemed to warrant the more careful study of the case of armored cables.

The main features that differentiate the latter from the former case are the difficulty of calculating the magnetic flux in the steel wires in view of the indefiniteness and variability of the air-gaps between them and the variability of the magnetic properties of armor wire.

The variety of iron armored single-conductor cables tested and the data obtained have not been sufficient to permit establishing a generally applicable calculating procedure for circulating currents and losses. While the data available cover sufficiently well for practical use the loss calculations for the few designs considered, iron armored cables of radically different design would probably require additional empirical data to be derived from tests, as a basis for the calculations. If the proper additional tests were made for a few other types of armor designs, a more general calculating procedure could probably be established.

A paper[1] is under preparation reviewing the knowledge at hand, and reporting the results of recent tests and analysis as a further step of progress toward a more general understanding of the problem.

In general the use of copper armor in place of steel will greatly reduce the losses in a submarine cable. In many cases either copper or iron armor is mechanically feasible; and the question as to which should be used in a given project will then be decided on an economic basis. The paper will include an analysis of the economic factors involved.

*Alternating-Current Electrolysis of Lead Cable Sheaths.* The use of single-conductor cables in separate ducts for three-phase circuits of high voltage has led to the adoption of various methods for the reduction of induced currents in the sheaths. These schemes entail a-c. potentials from the sheaths to ground of varying magnitudes and the question of whether electrolytic corrosion of the cable sheaths is likely to result from this practise is of considerable importance.

The phenomena involved in the alternating current electrolysis of lead are complicated by the chemical nature of the electrolyte. However, B. McCullum and G. H. Ahlborn state that in general under ordinary soil conditions electrolytic corrosion appears to be practically negligible when the period of the cycle is not greater than about five min. For the details of their findings reference should be made to Tech. Paper 72, Bureau of Standards 1916.

J. L. R. Hayden (TRANS. A. I. E. E., Vol. XXVI, p. 201) comes to the conclusion that electrolysis on alternating current rarely exceeds one-half of one per cent of the electrolytic action of the corresponding direct current.

Hayden also found that the superposition on an alternating current of 1.5 per cent of its value in direct current protected the lead against corrosion, the effect of course occurring when the cable was negative to the ground. E. R. Shepard (TRANS. *Am. Electro Chem. Soc.* 31, 239-51, 1921) in a paper entitled "Electrolytic Corrosion of Lead by Continuous and Periodic Currents," finds that with direct current the coefficient of corrosion in both tap water and earth decreases with an increase in current density, reaching a minimum of about 50 per cent for current densities of five milliamperes per sq. cm. The theoretical maximum of 100 per cent is found for low current densities of the order of 0.5 milliamperes per sq. cm. and less.

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[1] By O. R. Schurig, H. P. Kuehni, and F. H. Buller.

If, however, certain salts are present in the electrolyte so that the lead ions may react to produce an insoluble compound a comparatively large amount of corrosion may occur even with alternating current. Further investigations of this subject are under way and will doubtless add much valuable information to our present supply, which is none too complete.

It may also be appropriate to mention here that some trouble has been experienced with lead sheath corrosion due to the formation of a red lead oxide. The 1915 report of the N. E. L. A. Committee on Underground Construction indicated that reversals in polarity of the sheath of long duration would be effective in producing corrosion of this type. More recent results indicate that such corrosion may occur quite independently of electrolytic action, but whether or not d-c. or a-c. electrolysis may be an important factor in accelerating such corrosion is somewhat in doubt. This subject was discussed at a special meeting during the April Regional Meeting, which was held in Baltimore, and as a result of investigations now under way more detailed knowledge will probably soon be available.

*Summary.* While, as stated, no startling progress has been made during the year, attention is called to the significance of the many cooperative activities now under way, a few of which have been mentioned above. The greater attention being given to underground cable by operating companies as evidenced by this cooperative work, and the constantly increasing research work being done by the operating companies individually and by the manufacturers, all justify expecting continued improvement in high-tension cable.

*Papers Presented during Year.* Several papers have been presented during the year which are of interest to engineers concerned with the design and operation of underground cables. Among them may be listed the following:

*Joints in High Voltage Multiple Conductor Cable*, by Thos. F. Peterson, TRANS. A. I. E. E., Vol. 46, 1927, p. 963.

*The Influence of Residual Air and Moisture in Impregnated Paper Insulation*, by J. B. Whitehead and F. Hamburger, Jr., JOURNAL A. I. E. E., Sept. 1927, p. 939.

*High Voltage Measurements on Cables and Insulators*, by C. L. Kasson, TRANS. A. I. E. E., Vol. 46, 1927, p. 635.

*Electric Strengths of Solid and Liquid Dielectrics*, by Wm. A. Del Mar, W. F. Davidson, and R. H. Marvin, TRANS. A. I. E. E., Vol. 46, 1927, p. 1049.

*Influence of Internal Vacua and Ionization on the Life of Paper Insulated High Tension Cables*, by Alexander Smouroff and Leo Mashkileison, A. I. E. E. Quarterly TRANS., July 1928, p. 731.

*132,000-Volt Single Conductor Lead Covered Cable*, by P. Torchio, L. Emanueli, W. S. Clark, A. H. Kehoe, C. H. Shaw, J. B. Noe, and D. W. Roper, A. I. E. E. QUARTERLY TRANS., Vol. 47, No. 1, January 1928, p. 186.

### POWER LIMITS OF SYSTEMS

Further progress is reported in the development of methods for predetermining power limits of systems and of criteria for system stability. From this standpoint, important progress has also been made in synchronous machine theory.

A number of papers bearing on the problem of power transmission has been presented during the year. Three of these presented at the Winter Convention (bibliography references 1, 2, and 3) have added materially to the underlying theory as well as outlining methods for predetermining with practical accuracy those characteristics of synchronous machines which are of importance from the standpoint of stability. A paper on power limits with several machines connected to the system was presented at the Pacific Coast Convention (reference 4). A mechanical method of calculating power limits is described in a paper presented at Baltimore (reference 5).

Last year's report indicated the extent to which high speed or quick response excitation had been adopted as a means of preserving synchronism in a system during short circuits. The installations made to date are the Farmersville substation of the Southern California Edison Company, the Gatineau Falls Development of the International Paper Company, and the Conowingo Development of the Susquehanna Power Company. The experience obtained to date with these installations has been insufficient to draw any definite conclusions regarding their effectiveness in maintaining stability. Without such operating experience, the committee has no further statement to make except to repeat the opinion generally held, that there is a number of cases where quick response excitation may be advantageous. It is not a panacea for system troubles. The question of its application, of the quickness of response, and of the "ceiling" exciter voltage, should be determined by a study of the particular conditions of a given case. Certain limitations common to all systems, such as saturation effects and rotative speeds, have been covered in a recent article (reference 10). Although there may be cases where conditions would not warrant a special excitation system to obtain rapid voltage build-up, there are cases, nevertheless, which justify very special means to secure not only extraordinary quick response, but also a high value of exciter voltage. For illustration, such equipments have been purchased by the Philadelphia Electric Company as part of five 30,000-kv-a. condensers which are being installed at the Plymouth Meeting and the Westmoreland substations of Philadelphia Electric Company. No operating data, of course, are as yet available. Installations of this character have been described before the Institute and in the technical press (references 7 to 15, inclusive).

Further progress is reported in factory tests of power transmission, using voltage regulating devices, substantiating previous tests demonstrating the possibility of stable operation under a condition of dynamic or artificial stability, that is, at values of power considerably above the limit with fixed excitation (references 13 and 14). It is thus a promising development as regards increasing the maximum output of synchronous machines. It is expected that even if it is not necessary at the present time to transmit regularly values of power above the steady-state limit, there may be occasions when certain branches of a system may be momentarily loaded beyond the steady-state limit, due to switching operation, sudden load shifts, etc., and the devices referred to should prove beneficial under such conditions. Data have also been obtained indicating that these devices, in conjunction with exciters of appropriate characteristics, materially improve the transient stability of a transmission system, that is, the ability of a system to carry through short circuits, and that they assist in helping to steady down a system which has been set into violent oscillation as the result of a severe short circuit.

There is an urgent need for further field data. These data should take two forms:

a. Further tests on systems for which calculations have been made, as a check on such calculations.

b. Data secured during transients encountered in normal operation, by means of special recording devices, such as the automatic oscillograph and the high speed recorder. Preferably these data also should be obtained on systems for which calculations have been made.

Some work has already been done along the latter line, and has been reported to the Institute (reference 16). In addition, there is a need for further data on the total impedance in the path of short circuit currents flowing from conductor to neutral at the values of current ordinarily encountered in such short circuits. A method for obtaining these data, together with a discussion of the effect of ground resistance upon the stability problem, has recently been published (reference 17).

It is felt that in the problem of maintaining synchronism between all machines connected to a system during short circuits, very considerable benefit will be obtained by reducing as far as possible the magnitude and duration of the disturbance caused by a short circuit. It is not generally practicable to reduce the short circuit current by the introduction of series impedance in the path of load currents as this decreases the power limits directly. Since, however, most short circuits occur from line to neutral, considerable benefit may be expected from making use of means which limit the value of line to neutral short circuit current without increasing the impedance of the system to normal load current.

For illustration the following means are available:

1. In the case of an a-c. low voltage network by feeding the network from a number of small step-down stations, thereby limiting the current caused by a short circuit on the distribution system.

2. Grounding only part of the transformer banks at any one point.

3. The introduction of impedance devices in the neutral connection. Other means may be desirable in special cases.

In the belief that the trend in the future will be in the direction of reducing fault currents without increasing the impedance of the system to load currents, the committee therefore recommends that in the case of new systems or in the case of extensions to or changes in existing systems, consideration be given to means of reducing such fault currents.

For papers and articles reference should be made to the Bibliography (2) covering this subject.

### ACKNOWLEDGMENT

The material in this report has been obtained from a multiplicity of sources and includes contributions made through the courtesy of committees of other organizations as well as those of subcommittees and individual members of this committee. Without making a detailed acknowledgment, the chairman wishes to take this opportunity of expressing to the contributors as a group the appreciation of this committee as well as his own personal thanks for the generous manner in which they have all given so unstintedly of their time and information.

PHILIP TORCHIO, *Chairman.*

## Bibliography on Power Limits of Systems (2)

### REACTANCE OF MACHINES

1. *Synchronous Machines IV*, by R. E. Doherty and C. A. Nickle, TRANS. A. I. E. E., Vol. 47, No. 2, April 1928, p. 457.

2. *Calculation of Armature Reactance of Synchronous Machines*, by P. L. Alger, TRANS. A. I. E. E., Vol. 47, No. 2, April 1928, p. 493.

3. *The Reactance of Synchronous Machines*, by R. H. Park and B. L. Robertson, TRANS. A. I. E. E., Vol. 47, No. 2, April 1928, p. 514.

### STABILITY LIMITS

4. *Static Stability Limits and the Intermediate Condenser Station*, by C. F. Wagner and R. D. Evans, TRANS. A. I. E. E., Vol. 47, No. 1, January 1928, p. 94.

5. *Quantitative Mechanical Analysis of Power-System Transient Disturbances*, by R. C. Bergvall and P. H. Robinson, presented at Baltimore Regional Convention, April 19, 1928.

6. "Baum Principle of Transmission," by C. L. Fortescue, *Electrical World*, May 7, 1927.

### QUICK RESPONSE

7. "Quick Response Excitation for Alternating Current Machines," by C. A. Powel, *Electric Journal*, April 1927, p. 157.

8. "High Speed Excitation for Stability," Abstract of

paper presented before N. E. L. A. Apparatus Committee by C. A. Powel, *Electrical World*, May 21, 1927, p. 1061.

9. "High Speed Excitation for Generators," by F. G. Hamner, *Electrical World*, August 6, 1927, p. 263.

10. "Practical Considerations Affecting Quick Response Excitation for Salient Pole Machines," by P. H. Robinson, *Electric Journal*, February 1928, p. 65.

11. "Super-Excitation," by D. M. Jones, *General Electric Review*, December 1927, p. 580.

12. "Super Excited Condensers," by O. A. Gustafson, *Electrical World*, February 18, 1928, p. 349.

13. *Excitation Systems*, by R. E. Doherty, A. I. E. E. Quarterly TRANS., July 1928, p. 944.

14. *Voltage Regulators*, by C. A. Nickle and R. M. Carothers, A. I. E. E. Quarterly TRANS., July 1928, p. 957.

15. *Super Excitation*, by D. M. Jones, presented at A. I. E. E. Regional Convention at Baltimore, 1928.

SYSTEM DATA

16. *Transients Due to Short Circuits*, by R. J. C. Wood, L. F. Hunt, and S. B. Griscom, TRANS. A. I. E. E., Vol. 47, January 1928, p. 68.

GROUND RESISTANCE

17. "Characteristics of Ground Faults on Three-Phase Systems," by S. B. Griscom, *Electric Journal*, April 1927, p. 151.

## Discussion

**D. W. Roper:** Mention is made in the report of the underground 132-kv. cable installations in New York and Chicago. I think the report would properly be supplemented by a statement of the service record of that cable. There are approximately 36 mi. of cable in New York and 18 mi. of cable in Chicago. The latter installation has been in service nearly 13 months and the New York installation nearly 11 months. The total service record amounts to nearly the equivalent of 50 mi. of cable for one year and during this time there have been no electrical failures, a record which I believe is unequaled by any recent performance of any underground cable from the time when the first installation of a higher-voltage cable was installed in this or any other country.

The paper mentions also some trouble with red oxide of lead on underground cables in certain locations. There was a meeting at Baltimore to discuss the subject. The results of that meeting and subsequent experiments did not get reported to the Chairman in time to be included in this report and I thought they might be interesting.

The clue was given by a peculiar condition in Chicago, where a concrete conduit was cast in place. The conduit was so enclosed that air could not reach it readily. This conduit was connected to another conduit made of pre-cast sections and so located that water might drain from the first conduit into the pre-cast conduit. Corrosion was found on cables in both conduits, but mostly in the lower conduit.

In the disucussion at Baltimore it was brought out by cement experts that cement requires carbon dioxide for setting as well as moisture.

In the case of the monolithic conduit, there was abundant moisture, but apparently a deficiency of carbon dioxide. Evidently the carbon dioxide absorbed by the water seeping into the concrete structure from the surrounding earth was all given up to the outer portion of the concrete. The water, continuing its course through the concrete to the interior of the ducts, picked up the alkaline hydrates from the uncured concrete and then ran down through the conduit and into the other conduit. The alkaline hydrates attacked the lead sheaths principally in the pre-cured ducts, which are only slightly inclined. This was confirmed by analyses of the water taken from the ducts which show hydroxides of lead and calcium.

The action of these hydrates can be stopped temporarily by the application of carbon dioxide gas to the ducts or allow it to bubble up through the water in the ducts; but the relief obtained in this manner is only temporary. Analyses taken a few days after the application of the gas again show a dangerous amount of the alkaline hydroxides. The trouble has continued for over 15 months after the installation of the monlithic conduit, and a solution for the trouble has not yet been found.

In this case, where the corrosion was due to chemical action, the products of corrosion are generally from a yellow to a deep red color, while in mild cases of electrolysis extending over several years, the corrosion products range from a white to a light yellow in color.

The conclusion is that when ducts are cast in place at least a month should elapse to give the concrete time to set before cables are installed.

**Harold Michener:** I should like to say a little about vibration. We of the Southern California Edison Company think the subject of conductor vibration is very important and probably should be emphasized more than it is in this report. I think we have published more about our troubles due to conductor vibration than any other company. We feel that we have solved the problem, and that with the use of these vibration dampers we can hold any conductor so that it will not vibrate appreciably.

I think this should be considered very carefully in connection with the ground wires as well as in connection with the conductors. I would recommend particularly that those who are putting up ground wires in suspension clamps expecting them to prevent breaking of the ground wires at the points of support should keep very close watch of those points of support. We feel that when there is vibration the thing to do is to stop the vibration rather than try to put some arrangement at the points of contact that will ease off the deteriorating effect that the vibration has even though flexibility and easy entrance curvatures undoubtedly are of some benefit.

**M. T. Crawford:** Since submitting data to the committee from which the figures in Table I, Company 5, were compiled, I have secured additional data covering simultaneous years operation of another company's 110-kv. wood-pole transmission line running through the same territory. This line was built with a ground wire throughout, whereas the line shown in the committee report was without the ground wire. It is interesting to note that over a three-year period this line averaged 0.88 breaker openings per hundred miles per year, which is very close to the average of the values shown for the wood-pole lines without ground wires for Company 5 through the same period.

These lines are located in the Puget Sound region where lightning is comparatively infrequent, but with over a thousand miles of line and in a three-year period the results should be fairly indicative of the value of the ground wire and do not seem to show that the ground wire is economically justified under conditions obtained in this locality. As a result of this analysis, the Puget Sound Power & Light Company is now building additional 110-kv. wood-pole transmission lines about one hundred miles in length and no ground wire is being installed.

**Philip Torchio:** Numerous data have been collected in recent years regarding lightning disturbances on transmission lines and the preponderance of the evidence available indicates quite clearly that a great deal of protection may be expected from the use of ground wires. In some cases, such as the one mentioned by Mr. Crawford, the ground wire has not appeared to give the anticipated benefits and it is to be hoped that future records of operation and studies of the local conditions will disclose the reason for these variations. There are so many variables involved in studies of this kind that it is only by the analysis of records which cover a long period of time and which have been most carefully correlated with the local conditions that helpful deductions can be made. Fortunately, we now have the klydonograph which is of invaluable aid in carrying on these investigations.

# Protective Devices

## ANNUAL REPORT OF COMMITTEE ON PROTECTIVE DEVICES*

*To the Board of Directors:*

The principal work of the Committee this year has been—, *first*, arranging for and the actual preparation of papers for presentation at meetings of the Institute, of which there have been one or more presented at practically every meeting of the Institute, and *second*,—the work of standardization, the result of which work is reported below.

The work of the Committee has been carried on by subcommittees, each under the direction of its own chairman, and after the first organization meeting at New York in September further meetings have been held by the subcommittees individually. The subjects covered and the chairmen in charge of the subcommittees are as follows:

Current Limiting Reactors, A. H. Sweetnam, Edison Elec. Illum. Co., Boston, Mass.

Communication Circuit Protection, H. W. Drake, Western Union Tel. Co., New York, N. Y.

Industrial Control Equipment and Service Protection, R. C. Muir, General Electric Co., Schenectady, N. Y.

Lightning Arresters, J. A. Johnson, Niagara Falls Power Co., Niagara Falls, N. Y.

Circuit Breakers, Switches, and Fuses, J. M. Oliver, Georgia Power Co., Atlanta, Ga.

Reactors, W. H. Millan, Union Elec. Light & Power Co., St. Louis, Mo.

### SUBCOMMITTEE ON INDUSTRIAL CONTROL EQUIPMENT AND SERVICE PROTECTION

The subcommittee has prepared a revision of the A. I. E. E. Industrial Control Standards. This revision is in process and not finished sufficiently to be presented at this time.

### SUBCOMMITTEE ON COMMUNICATION CIRCUIT PROTECTION

The subcommittee has arranged for several papers and is giving active study to the question of standardization.

Reports of other subcommittees attached.

## Proposed Standards for Lightning Arresters

## No. 28

*Prepared by Subcommittee on Lightning Arresters*

Corrected to April 12, 1928

### SCOPE

The standards in this section shall apply to all types of lightning arresters embraced within the classifications given in paragraphs 28-100 and 28-101.

### SERVICE CONDITIONS

28-1 *Usual Service Conditions.*—Apparatus conforming with these standards shall possess its specified characteristics and be capable of successful operation:

a. When and where the ambient temperature does not exceed 40 deg. cent. for air.

b. Where the altitude does not exceed 1000 meters (3300 ft.).*

28-2 *Unusual Service Conditions.*—The use of apparatus under conditions other than noted under (28-1) shall be considered as special. Other conditions which may require special consideration are:

a. Temporary overvoltage (such as may occur due to apparatus or line regulation, and/or generator over-speed, following sudden loss of load).

b. Sustained overvoltage (such as may result from accidental arcing grounds on one-phase of a circuit of which the neutral either is not earthed or is earthed through a considerable resistance).

c. Sustained overvoltage (such as may appear on non-earthed circuits by induction from unbalanced parallel higher voltage circuits in close proximity, or by contact with circuits of higher voltage).

d. Sustained overvoltage caused by removal of neutral connection to earth in combination with a grounded conductor (such as may occur on part of a system when it is disconnected from, or located at a great distance from, the part of the system having the neutral earthed).

e. Exposure to damaging fumes, vapors, or dusts.

f. Exposure to salt air.

g. Operation in damp places or climate.

h. Exposure to steam.

i. Exposure to excessive oil vapor (which may, by condensation and accumulation, change the characteristics of spark-gaps, or be ignited by a spark and produce a conducting flame).

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**COMMITTEE ON PROTECTIVE DEVICES:**

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H. R. Summerhayes, Vice-Chairman,
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H. P. Sleeper,
A. H. Sweetnam,
F. D. Wyatt.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

*The limitations of temperature and altitude are adopted for the purpose of uniformity with other standards. Manufacturers consider as standard an altitude up to 1214 meters (4000 ft.).

j. Exposure to excessive dust.
k. Exposure to explosive gases or dusts.
l. Exposure to abnormal vibration or shocks.

Where such conditions exist, it is recommended that they be brought to the manufacturer's attention.

### DEFINITIONS

28-50 *Lightning.*—Lightning is an electrical discharge* occurring in the atmosphere from cloud to cloud, between cloud and earth or within a cloud.

28-51 *Lightning Surge*†.—A lightning surge is a transient electrical disturbance in an electric circuit caused by lightning.

28-52 *Test Surge.*—A test surge is an electrical impulse of specified characteristics produced for the purpose of laboratory tests.

28-53 *Lightning Arrester.*—A lightning arrester is a device providing a path for electric current between an electric circuit and earth through which, upon occurrence of a lightning surge, current will be conducted in sufficient amount to reduce the over potential of the circuit caused by the surge, and thereafter will cease to be so conducted.

28-54 *Discharge Current.*—The discharge current of a lightning arrester is the surge current which flows through the arrester to earth upon the application to its terminals of a lightning or test surge.

28-55 *Follow Current.*—When surge current passes through a lightning arrester there is formed a conducting path through which generated current‡ may also flow. The generated current which follows the surge current through the arrester in this manner is called the "follow current."

28-56 *Ground (Noun and Verb).*—A conducting connection, often accidental, between an electrical circuit and earth, or any other conducting or partly conducting structure or material.

The term "ground" is used loosely, There may be no connection with the real ground or earth. For example, when a porcelain insulator is punctured and a conducting path is formed between the supported line wire and the supporting metallic pin it is customary to say the line is "grounded" to the pin in spite of the fact that the pin may be thoroughly insulated from earth by a dry wooden pole and crossarm. An overhead ground wire is said to be "grounded" to a steel tower although the tower may not be earthed.

28-57 *Earth (Noun and Verb).*—An intentional electrical connection or contact with the earth.

Unlike "ground," the word "earth" when used in this sense is an unequivocal term having but the one meaning. Earths are usually made by driving one or more metallic pipes or rods into the earth; by burying metal plates or other conducting material in the earth with suitable connections thereto or by connecting with metallic materials (such as water pipes) already buried in the earth. The resistance of an "earth" depends in general upon the extent of contact with the soil, the degree of moisture present, the nature of the soil and its soluble content.

28-58 *Series-Gap.*—A spark-gap connected in series with a lightning arrester, to keep the circuit through the arrester open under normal conditions and to close the circuit for the lightning discharge by sparking.

28-59 *A Horn-Gap.*—Is a spark-gap equipped with metal horns to assist in interrupting follow current. Such a gap is sometimes used as a series-gap with a lightning arrester.

28-60 *A Protected Series-Gap.*—Is a series-gap protected from rain and other precipitation by a roof or cover.

28-61 *Characteristic Element.*—The characteristic element of a lightning arrester is that part of the arrester whose function it is to control the discharge current, and suppress the follow current.

28-62 *Cathode Ray Oscillograph.*—An oscillograph in which the moving element consists of a pencil of cathode rays. Such a moving element has no inertia and hence can be made to record accurately transients of extremely short duration.

28-63 *Microsecond.*—A time interval of one-millionth ($10^{-6}$) second.

### CLASSIFICATION

28-100 *Classification According to Use.*—Lightning arresters may be classified according to the uses for which they are designed and intended, as follows:

a. As to kind of circuit to be protected; as power or communication type.

b. As to location; as line or station type.

c. As to weather protection; as indoor or outdoor type.

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*When such a discharge between cloud and earth terminates on a transmission line, apparatus, or other objects with which we are concerned, it is called a "direct stroke" of lightning.

Although direct strokes may be destructive, they usually strike electrical systems only in the transmission circuits, where, in the present state of the art, it is not economic to protect completely against them. Lightning arresters are not, in general, designed to protect against direct strokes.

†In relation to the circuit as a whole a lightning surge usually takes the form of a traveling wave or transient in space. In relation to any given point of the circuit, however, such a surge manifests itself as a transient in time. A lightning surge manifesting itself as such a time transient at a point in a circuit may be caused by:

1. A direct stroke of lightning at or near the point.
2. A traveling wave caused by a direct stroke elsewhere on the circuit.
3. Release of bound induced charge at the point (as by nearby discharge of cloud).
4. A traveling wave resulting from release of bound charge elsewhere on the circuit.

‡In these standards the current, voltage, and frequency that are supplied to the circuit by the source of power are called respectively, generated current, generated voltage, and generated frequency.

d. As to nature of generated circuit current; as d-c. or a-c. type.

e, As to system connection; as for earthed or non-earthed neutral.

28-101 *Classification as to Control of Follow Current.*—There are two general types:

a. Valve Type: A valve type arrester is one whose characteristic element has a high effective resistance at normal line potential, which resistance decreases with increasing potential and returns to its original value as the applied potential returns to normal. These characteristics result, in general, in suppression of follow current.

b. Follow Current Type: A follow current type arrester is one which permits follow current to flow. Some arresters of this type effect the interruption of the follow current by means of the operation of some current interrupting device, and others by means of the cyclic nature of the generated voltage in combination with some property of the characteristic element.

### Rating

28-150 *Rating Defined.*—A rating of a machine, apparatus, or device is an arbitrary designation of an operating limit. Lightning arresters are given voltage ratings only and are rated in terms of generated r. m. s. circuit voltage.

28-151 *System Voltage Rating.*—The system voltage rating of a lightning arrester is the rated r. m. s. system voltage upon which the arrester is intended to be used. This rating will usually determine the general insulation requirements of the arrester.

28-152 *Maximum Voltage Rating.*—The maximum voltage rating of a lightning arrester is the maximum operating r. m. s. voltage to which the arrester should be subjected.[*] This rating determines the breakdown voltage of the series-gap and the protective characteristics of the arrester.

### Characteristics and Performance

28-160 *Characteristics Enumerated.*—The suitability of a lightning arrester for its purpose depends upon the degree in which it possesses three characteristics or properties, *viz.*:

1. Protective ability of which its "protective characteristic" is a measure.
2. Ability to perform its operating cycle.
3. Permanence, involving both its ability to retain its protective ability and to repeat its operating cycle. The measure of this latter ability involves both the frequency and number of such repetitions.

28-161 *Protective Characteristic.*—The protective ability of a lightning arrester under given conditions[†] depends upon the voltages to which it limits the surge and the times during which it permits such voltages to be maintained. Since protective ability is a function of both voltage and time, it cannot well be expressed by a single quantitative value, but is better indicated by a curve with time and surge voltage as coordinates. Such a curve obtained under controlled test conditions is the "protective characteristic"[‡] of the arrester under those conditions, and when obtained under the standard test conditions specified under 28-201 shall be called the "Standard Surge Protective Characteristic" of the arrester.

28-162 *Operating Cycle.*[**]—The operating cycle of a lightning arrester embraces the following actions:

1. At the start of the cycle the circuit through the arrester is open thus permitting no current to flow. (In arresters without series-gaps a very small current may flow.)
2. Upon the occurrence of a lightning surge or other transient potential exceeding a certain voltage the series-gap breaks down and/or the effective resistance of the characteristic element decreases, permitting surge current to pass through the arrester.
3. Surge current continues to flow so long as sufficient surge potential persists and may be followed by generated current—depending upon the type of arrester.
4. Upon cessation of the surge potential, or its reduction to some lower value, surge current

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[*] Since a lightning arrester is intended as a protective device against transient overvoltage, its breakdown voltage is necessarily lower than that of the apparatus it is designed to protect. Its voltage rating, therefore, must have special consideration. Increasing the generated voltage at the terminals of an arrester above its maximum rating reduces its factor of safety and may result in its destruction at the time of discharge. On the other hand, choosing an arrester of a rating above the usual maximum voltage of the circuit to meet abnormally high generated voltage on the system reduces the effectiveness of the arrester as a protective device.

[†] The ability of a lightning arrester in service to protect apparatus against lightning surges depends in part upon certain conditions external to the arrester itself. Among such conditions are:

a. The characteristics of the incoming surge.

b. The surge impedance of the circuit over which the surge arrives.

c. The number and surge impedance of circuit branches starting at or near the point of connection of the arrester.

d. The length and impedance to surge current of connection from circuit to arrester and from arrester to earth.

e. The distance along all circuit branches between point of connection of lightning arrester and the apparatus to be protected.

f. The characteristics of the apparatus to be protected.

[‡] The relative effects of the magnitude and the time of application of voltage in causing breakdown of insulation are not as yet definitely known. A "protective characteristic" of a lightning arrester is a measure of its ability to protect against the surge by which it was obtained, but cannot be evaluated in absolute terms until insulation characteristics are better known than at present.

[**] The successful performance by a lightning arrester of its operating cycle is in no degree an indication of its protective ability which depends upon other characteristics and conditions.

ceases to flow and at some time thereafter the follow current—if present—is interrupted, thereby restoring the arrester to a condition of open circuit.

At the completion of its operating cycle an arrester should be in condition to repeat the cycle immediately, although it shall not be assumed that the cycle may be thus repeated indefinitely.

The performance of its operating cycle should not appreciably alter the protective characteristic of the arrester.

### TESTS

28-200 The following tests shall apply to all arresters except those with large electrostatic capacity used without series gaps.

### TESTS FOR PROTECTIVE CHARACTERISTICS

28-201 *Standard Surge Protective Characteristic.*—Tests to determine the standard surge protective characteristic of a lightning arrester shall be made by the use of a test surge, the voltage of which shall be unidirectional and shall rise at the rate stated in 28-202 until the arrester begins to discharge, after which the discharge current through the arrester shall rise at the rate of 100 amperes per microsecond to a crest value of 1000 amperes and thereafter decrease to 500 amperes in not less than 10 microseconds.

28-202 *Rate of Voltage Rise of Standard Test Surge.*—The rate of voltage rise of the standard test surge prior to beginning of arrester discharge shall be as follows:

a. For arresters or arrester sections of low voltage rating up to 11 kv.-100 kv. per microsecond.

b. For arresters or arrester sections of ratings higher than 11 kv. the rate of rise of voltage of the standard test surge shall be increased proportionately, *i. e.*, 200 kv. per microsecond for a 22 kv. arrester, etc.

28-203 *Parts of Arresters to be Used for Protective Characteristic Tests.*—For determining the protective characteristics of low-voltage arresters up to 11 kv. system voltage rating, the entire arrester shall be used (single pole). For arresters of higher voltage ratings tests may be made on suitable sections of the arrester whose combined voltage ratings do not exceed 11 kv., with series-gap set for proportionate sparking voltage, and the results extrapolated.†

28-204 *Other Protective Characteristics.*—Tests for protective characteristics with test surges other than standard may be made, but in every such case the exact characteristics of the test surge employed, including the rate of voltage rise prior to beginning of arrester discharge, rate of current rise thereafter, crest value of current, and duration or rate of decay of current, shall be stated or shown by suitable cathode ray oscillograms.

28-205 *Use of Cathode Ray Oscillograph.*—Protective characteristics of lightning arresters shall be determined by the use of a cathode ray oscillograph.

### TESTS FOR PERFORMANCE OF OPERATING CYCLE

28-210 *Parts of Arrester to be Used.*—Tests for the performance of its operating cycle may be made upon a single pole of the arrester and in the case of valve type arresters of sectional construction may be made upon suitable low voltage sections at proportionate generated voltages and with proportionate series-gaps.

28-211 *Characteristics of Test Circuit.*—The arrester shall be connected across a circuit of voltage equal to the maximum rated voltage of the arrester or arrester section under test and of such power capacity and impedance that the generated voltage across the arrester shall not be decreased more than five per cent below rated voltage for a period of more than one-half cycle of generated current at the crest of the follow current. A non-inductive load, which in the case of higher voltage arresters may be a transformer with loaded secondary, shall be connected across the arrester terminals, so adjusted that generated power current of the order of five to ten amperes shall be flowing past the arrester during the test.

28-212 *Initiation of Discharge.*—Discharge shall be initiated by a test surge so timed as to start follow current as early as possible in a half cycle of generated voltage. If no follow current flows the surge should strike at the crest of the generated voltage wave.

28-213 *Oscillographic Record.*—Voltage and current relations during the period of follow current flow shall be determined by the use of an oscillograph, the electromagnetic type being suitable for this purpose.

28-214 *Standard Operating Duty.*—The standard operating duty of a lightning arrester shall be ten operating cycles at intervals of one minute.

28-215 *Condition of Arrester at Completion of Standard Operating Duty.*—At the completion of its standard operating duty the arrester shall be in the following condition:

a. The breakdown voltage of the series-gap shall not be appreciably altered.

b. The protective characteristics of the arrester shall not be appreciably altered.

c. The arrester shall be in condition to repeat its operating duty, though not necessarily indefinitely.

d. No part of the arrester shall be injured, either mechanically, electrically, or thermally.

### DIELECTRIC TESTS

28-220 *Standard Test Voltages.*—The standard test voltage for lightning arresters, except as otherwise specified, shall be an alternating voltage having an r. m. s. value as follows:

a. Lightning arresters rated at 600 volts or less—twice rated voltage plus 1000 volts.

b. Lightning arresters rated above 600 volts, 2¼ times rated voltage plus 2000 volts.

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†In the present state of the art more accurate results can be secured by test on low voltage sections and extrapolating, than by direct test on higher voltage units requiring a voltage divider to use the oscillograph.

28-221 *Duration of Application of Test Voltage*—

a. For insulation consisting of porcelain, glass, or other similar vitrious materials the test voltage shall be applied continuously for one minute.

b. For insulation consisting of wood, paper, fibre, and other similar organic materials, whether or not impregnated, the test voltage shall be applied continuously for 10 min.

c. Standard arresters produced in large quantities for which the standard test voltage is 2500 volts or less, may be tested for one second with a test voltage 20 per cent higher than the one-minute test voltage.

28-222 *Conditions under which Dielectric Tests shall be made.*—

a. For arresters intended for indoor service and for all arresters rated at 600 volts or less, dielectric tests shall be applied with the arrester dry and clean, and at ordinary room temperature.

b. For arresters intended for outdoor service dielectric tests shall be made under precipitation of two-tenths in. (5.08 mm.) per min. at an angle of 45 deg. from the perpendicular with water having a resistivity as low as 7000 ohm cm.

c. When necessary for the protection of the characteristic element during test or in order to attain the test voltages herein named, a portion or all of the characteristic element may be removed during the dielectric tests. In case the characteristic element cannot be removed without also removing its insulating container, dummy container sections of similar characteristics, containing no characteristic element, may be substituted to the extent necessary to carry out the dielectric test.

28-223 *Where Dielectric Tests are to be Made.*—Unless otherwise agreed upon dielectric tests shall be made at the factory.

28-224 *Points of Application of Voltage.*—Test voltage of suitable value shall be applied between the following points.

a. With series-gaps short circuited (and characteristic element removed if necessary—see 28-222 (c)) the test voltage shall be applied between each line terminal and ground, and between each pair of line terminals.

b. With series-gap removed or sufficiently enlarged to prevent breakdown, voltage shall be applied across the terminals of the insulator or insulating material normally in parallel therewith. For the purpose of fixing the test voltage for this test the rated voltage of the insulation in parallel with the series-gap shall be considered to be two-thirds of the generated frequency breakdown voltage of the gap at its normal setting.

c. Insulators so located as to be subjected at any time to only a proportionate part of the voltage between line terminal and ground shall be assumed to be rated proportionately and shall be subjected to proportionate dielectric test voltage.

28-225 *Frequency and Wave-Shape of Test Voltage.*—The frequency of the test voltage shall be not less than 25 cycles per sec. A sine wave shape is recommended. The test shall be made with alternating voltage having a crest value equal to the square root of two times the specified test voltage.

28-226 *Measurement of Voltage.*—The voltage for dielectric test shall be measured in accordance with the section of the Standards entitled "Standards for the Measurement of Test Voltages in Dielectric Tests."

### CONSTRUCTION DATA

28-250 *Name Plate Markings.*—The following minimum information shall be given on the name-plates of all station and line type arresters for power service.

a. Manufacturer's name and address.

b. Manufacturer's type and designation number.

c. Voltage ratings (system and maximum).

d. Proper setting of series-gap if adjustable.

28-251 *Published Data.*—The following data in addition to information on the name-plate shall be given in manufacturer's publications:

a. Weight.

b. Amount of oil and/or other liquid required (if any).

c. Such dimensions as required for installation.

## CURRENT LIMITING REACTORS

### *Report of Subcommittee*

Two interesting developments in current limiting reactor practise involve the use of reactors which are oil-immersed in steel tanks. One development involves the use of a three-phase reactor, oil-insulated, self-cooled, while the other involves a single-phase unit, oil-insulated, and water-cooled. The advantages claimed for these designs are that foreign material cannot be drawn into the windings and that the equipment can be used with the highest factor of safety either for indoor or outdoor service.

The single-phase equipments are designed for installation as 22-kv. bus section reactors, introducing a reactive drop of 9.2 per cent when passing 90,000 kv-a. No live parts are exposed, as the coil is mounted in a steel tank, and lead covered cable is to be "wiped" to glands bolted to a junction box, which in turn is bolted to the tank. This method of attachment makes possible the removal of the reactor from the circuit without disturbing the "wiped" joints. Each cable terminal is so insulated that cable sheath currents cannot flow through the tank to ground.

The tank is provided with a conservator, pressure relief pipe, oil gage, thermometer, and standard gage trucks.

The magnetic flux of the reactor which would normally link the steel tank, causing large losses, is neutralized by utilizing the copper cooling coils as a short circuited winding, (the intake and discharge ends of the cooling coils being joined) thus acting as a flux shield. The potential developed in this shield causes a current to flow, which in turn develops an equal but opposite flux. Therefore, no flux enters the tank, and no losses are developed. The material of the cooling coils is a high-conductivity copper tubing of adequate cross-sectional area to permit such currents to flow as will develop the required flux. To neutralize the flux of the reactor coil the current in the shield is limited to a definite value by the inherent reactance of the cooling coils. The losses in the shield are limited by properly proportioning the cross-section of the shield.

### RELAYS

#### *Report of Subcommittee*

Three papers have been presented to the Institute during the current year under the auspices of this subcommittee as follows:

> *Developments in the Impedance Relay and its Application*, by H. A. McLaughlin and E. O. Erickson.
>
> *Application of Relays for the Protection of Power System Interconnections*, by L. N. Crichton and H. C. Graves.
>
> *A Carrier Current Pilot System of Transmission Line Protection*, by A. S. Fitzgerald.

The second paper listed was presented both at the Chicago and New Haven Regional Meetings.

The work of this year's subcommittee has consisted chiefly of reviewing the work of previous years and attempting to crystalize work which has been started. In this connection attention is called to the matter of standardizing relay acceptance test specifications. A group of last year's subcommittee submitted tentative test specifications in the annual report and expressed the hope that interested engineers would forward their comments to this subcommittee so that a tentative "Standard" could be submitted at this time.

Very few comments have been received and therefore it is thought advisable to submit the recommendation again with modifications herein:

The following acceptance tests are offered for consideration:

1. The complete name-plate data of the relay should be taken, including the name-plate data of its resistor, if it has one.
2. The relay mechanism should be carefully inspected to see that all parts function properly, and to insure that there are no loose screws or other parts.
3. The internal wiring of the relay should be checked to determine that it agrees with the specifications, and that the physical arrangement is satisfactory.
4. Dielectric strength tests should be made between each operating coil circuit and the other circuits grounded to the case, and between the trip circuit and the relay case. Tests should be made at 1500 volts, 60 cycles and should last for one minute.
5. The gap lengths between the various contacts should be measured to make sure that they agree with specified values.

A suggested specification is given below:

| Relay type | Minimum allowable gap | | |
|---|---|---|---|
| | Main contacts | Auxiliary relay contacts | Lever setting |
| *IA* | 1/16 in. | .... | 1 div. |
| *CO* | 1/16 in. | 1/8 in. | 1 div. |
| *CR* | 1/16 in. | 1/8 in. | 1 div. |
| *IK* | 1/16 in. | 1/8 in. | .... |
| Bellows | 1/4 in. | .... | .... |

6. The relay should be operated on all of its taps to make sure that it operates properly and in accordance with specifications.

Some typical specifications are given below:

a. Overcurrent relays should operate within five per cent of the marked tap values.

b. The directional element of directional relays should not move with either current or potential only applied.

c. The directional element of type *I K* power directional relays should operate at 3 volts (across the potential coil, excluding any resistors), 8 amperes (single phase, unity power factor), in 0.40 sec. or less.

d. The directional element of type *CR* power directional relays should operate at 3 volts (across the potential coil excluding any resistors), 8 amperes (single phase, unity power factor) in 0.25 sec. or less.

e. The directional element of type *CR* ground directional relays should operate at 110 volts, 0.5 ampere (single phase, unity power factor), in 0.25 sec. or less.

f. Directional relays should not rebound when the rated voltage is maintained on the relay while 50 amperes are interrupted.

g. Directional relay contacts should stay closed after making initial contact when closing under 50 amperes at rated voltage.

7. The relay calibration curve should be obtained on one tap only. The calibration curve should be carried up to at least five times the pick-up value of the relay. During this test it should also be determined if the relay chatters at the higher current values used. Chattering tests on bellows type relays should be made at 25 cycles, while on induction relays, rated frequency should be used.

8. After Test 7 is completed, the relay contacts should be examined to make sure that there is no pitting. It is sometimes found that contacts

have a tendency to freeze after several operations. In order to make sure that this does not happen, the tripping contacts should be made to make and break currents of values of the order they will make and break in service.

9. Tests should be made to determine that the operation indicator functions with currents of the magnitude available in service.

10. On directional relays the polarity should be checked. On a single-phase, unity power factor test, instantaneous polarity in the same direction on the current and potential coils should cause an *IK* relay to close its contacts, whereas, under the same conditions a *CR* relay should hold its contacts open.

11. Zero torque tests should be made to determine the absence of disk rotation with either potential only, or current only applied to the relay. When current alone is used, a value ten times the minimum tap setting should be used. The zero current test should be made with rated voltage on the potential coil.

12. The volt-ampere consumption and power factor, or the resistance and reactance of the various coils of the relay should be determined. This will determine the burden the relay will impose on its instrument transformers. Burden should be calculated on a 5-ampere basis for current coils, and on a 110-volt basis for potential coils. Measurements should be made at rated frequency.

13. Vibration tests should be made to determine that the relay will not close its tripping contacts when it is subjected to external shock or vibration. During this test the behavior of the operation indicator should also be noted.

14. Heat tests should be made on the relay coils to make sure that they will not exceed the limits specified by the A. I. E. E. Standards. The heat tests on the current coils should be made at rated current. The heat tests on the potential coils of power directional relay should be made at rated potential. The heat tests on the potential coils of ground directional relay should be made at 190 volts, and should last only for five minutes. The reason for this short time test is that under normal operating conditions the potential coils of such relays have no potential impressed upon them, but under conditions of ground, as much as 190 volts may be obtained in circuits whose normal voltage is 110.

15. The effect of ambient temperature upon the relay characteristics should be determined over the range of temperatures likely to be met with throughout the various seasons.

16. The effect of the surrounding atmosphere (excessive dampness, and fumes, etc.) upon the relay characteristics should be determined.

Another item discussed by this subcommittee during the last two years was the matter of name-plate data. In general it is agreed that the following information should be available.

a. Descriptive name of relay.
b. Nominal operating current, voltage, or both.
c. Frequency.
d. Manufacturer's type or style designation.
e. Manufacturer's name or trade mark.

In addition to the above the polarity of directional relays should have studs marked in the same manner as are terminals of instrument transformers. It is further recommended that the following information be available on the card which is usually attached to the relay when furnished.

f. Calibration curve or time setting chart.
g. Volt-ampere consumption and power factor (or resistance and reactance of the various coils).
h. Interrupting capacity of tripping contacts.
i. Resistance values of all resistances furnished with the relay. These values should also be stamped on the name-plate of the resistor.

As questionnaires are unsatisfactory and undesirable, a request is here made for comments on the foregoing.

During the past year many new relay developments have appeared.

The carrier-current pilot protective system has been called to the attention of the engineering fraternity by Mr. Fitzgerald who assures us that this system offers practically all of the advantages of the well tried pilot-wire system without its most undesirable features.

Induction type relays have been developed for use as power-factor relays, temperature relays, for control of reactive kv-a. meters, and for control of street lamp circuits by carrier current. Also a new induction type relay has been developed to perform on the impedance principle for transmission line protection. This relay has its restraining coil designed on the induction disk rather than the plunger principle.

A speed control relay is now used to facilitate the synchronizing of turbine driven generators. It has double-throw contacts operated by Warren synchronous motors through a differential gear in such a way that if one motor is faster than the other, one contact is closed, and, if slower, the other contact is closed. One motor is connected to the bus and the other to the machine being brought up to speed. The contacts control the governor and increase or decrease the machine speed until it corresponds practically to the bus frequency, at which point the machine may be synchronized by another relay or by the operator.

A new polyphase network relay has been developed and along with other things provides a most ingenious method of quickly replacing or testing the relay unit.

Attention has been called to the need of development of relays along certain lines and we set forth below the specific needs which have been mentioned:

1. A multi-contact relay of the plunger type of a size between the present overcurrent plunger

relay and the relay used as an oil breaker closing relay. This device should be either "latching" or "electric release." The contact head should be designed for a complete interchangeability of front and back contacts.

2. A d-c. voltage relay whose pick-up and drop-out values can be accurately adjusted, which will not be affected by a reasonable amount of vibration and whose calibration will not vary by "soaking" or by reversal of potential.

3. Further development of timing relays is suggested as they seem to be the most doubtful. The fan type is somewhat weak mechanically and is limited in length of time. The bellows type is difficult to adjust and will not stay in adjustment as it is easily affected by dirt, temperature, etc. There is considerable distance between the type enumerated above and the expensive motor operated devices. A need is felt for something in between.

4. For automatic transformer stations relays are needed which will measure the total station load. This often results in a requirement for a relay having adjustable back contacts for 50 per cent to 90 per cent of the operating value and having current coils capable of carrying continuously three or four times the operating value. Also these relays should have independent make and break contacts.

5. A reverse current relay is needed having greater sensitivity. For example, it is quite difficult to find a relay which will carry continuously the load current of a generator and yet will operate on the small reversal due to the machine motoring.

6. An impedance relay should be developed for ground protection where the ground current is less than the line load current. Three years ago Mr. W. W. Edson suggested using a *CZ* relay with the voltage restraining element reversed so that it could be operated by the residual voltage of a star-delta potential transformer bank.

Late in the year this subcommittee was charged with the duty developing Standards for Relays and the preliminary draft of September 1923 was resurrected to be worked over. This work has been started but the best that can be hoped for is to have a suitable foundation laid down for the successors of this subcommittee next year.

Along with this to the successors of this subcommittee is recommended:

1. A study of the operating experience due to the use of low-tension potential transformers for relaying high-tension lines where the voltage vectors are not an exact reproduction of what is taking place in the lines protected. The various compensator arrangements are too complex to be 100 per cent reliable.

2. Further study in the matter of relaying a transmission system having two parallel lines which may work in parallel or independently. Various cross-connected schemes will meet the parallel condition but they fail on the second. Pilot wires would be suitable but they are expensive. Impedance relays are not suitable for short sections of lines and they require special consideration when the expected ground currents are less than the load currents.

3. A study of the operating experience in the use of polyphase versus single-phase directional relays.

It is recommended that technical papers be obtained for presentation to the Institute of the three subjects named above.

F. L. Hunt, *Chairman.*

## Discussion

**K. B. McEachron:** In setting up standards for determining the protective characteristic of lightning arresters two points of view must be considered. First, what kind of duty is imposed by the surges which can come along connected circuits, and second, what can be produced and measured in the laboratory.

It seems probable based on field studies that voltages of the order of 2,000,000 volts may be reached in times of the order of 1 to 10 microseconds. The minimum time may be somewhat less and the maximum somewhat more than that given as no accurate measurements are yet available.

For a 220-kv. arrester this means, assuming 1 microsecond as the time to rise, a rate of voltage rise of 2,000,000/20 or 100 kv. per microsecond for each 11 kv. of rating. This it will be noted is the rate given in Section 28-202. Assuming, however, that the same potential gradient exists over an 11-kv. line half as high above the ground as the 220-kv. line, then the rate of potential rise will be 1000 kv. per microsecond or ten times the rate of voltage rise on the 11-kv. arrester as for the 220-kv. arrester when the transmission conductor is in the same electrostatic field.

It is feasible in the laboratory at the present time to produce impulses rising at the rate of 100 kv. per microsecond, but it is not feasible to produce impulses rising at the rate of 1000 kv. per microsecond, and yet have the wave front reasonably free from large oscillations.

If tests were made involving only potential rise, a wave rising at the rate of 1000 kv. per microsecond or 100 kv. in 0.1 microsecond might be obtained reasonably free from oscillations, but arrester testing requires the production of large currents in very short spaces of time which is not a condition conducive to steep rates of potential rise without excessive oscillations.

The traveling-wave theory states that the current in the traveling waves reaches its crest value at the same time that the voltage reaches its crest value. Going back again to the 220-kv. transmission line,—if the surge impedance be taken as 500 ohms and the arrester resistance also be considered as constant and equal to 500 ohms, then the current traveling in the conductor and through the arrester rises to a crest value of 2,000,000/500 or 4000 amperes in 1 microsecond. This assumes that the traveling wave has a crest potential of 2000 kv. and that the arrester is at the end of the line with no branch circuits.

In the present state of the art it is not possible to obtain a rate of current rise even approaching a figure of 4000 amperes per microsecond and still maintain reasonable freedom from oscillations and be able to record the phenomena on the oscillograph. To obtain such rates of current rise means little or no resistance in the circuit and very small inductance. Such a decrease in resistance means serious oscillation.

It seems desirable, therefore, to arrange the surge so that a current which is measurable and which can be obtained without excessive oscillations be chosen, and 100 amperes per microsecond seems about as high a rate as present methods and technique will allow. The crest value of 1000 amperes may in my opinion be subject to some variation, as for instance plus or minus 10 per cent, but the current should not decay too fast and the specification that the current shall decay to 500 amperes in a time not less than 10 microseconds is not unreasonable.

To specify a voltage wave when testing arresters is not sufficient because this only determines the breakdown voltage of the arrester. The second phase of arrester operation depends on the rate of current rise, the maximum current, and the duration of the current.

Since this is true it seems that the proper comparative test is to apply the same rate of potential rise, the same rate of current rise, and the same maximum current to all arresters, allowing the potential during this current flow to vary depending on the arrester itself and not on the impulse circuit to which it happens to be connected.

If impulse tests are to be made on insulation it is only necessary to consider rates of potential rise and a wave specified on the basis of maximum potential and time required to reach this potential would be sufficient as long as the breakdown occurs on the front of the wave. For such a test it would probably be desirable to specify also an exponential voltage rise.

For arrester testing such a specification is not sufficient. The maximum value of open circuit potential of the applied wave is not important. With the arrester the rate of voltage application up to the time when current begins to flow through the arrester is important, but what the voltage would have been if the arrester had not broken down has little or nothing to do with the characteristic of the arrester after it did become conducting. The remainder of the arrester performance after becoming conducting is dependent on the current-time relations. Thus sphere-gap measurements are not enough for the proper determination of the arrester characteristics, and I believe that it is a distinct step forward to specify the use of the cathode-ray oscillograph for the accurate determination of the arrester characteristics with respect to voltage, current, and time.

The manufacturer of lightning arresters does not make a practise of conducting complete tests such as outlined in the proposed standards on all arresters. Such complete tests are made on all new designs but it is felt that to take cathode-ray oscillograms, for instance, on all arresters would make an unnecessary addition to the cost of the arresters.

The proposed standards do give the user of lightning arresters a set of standards which when applied to arresters will allow him to make comparisons on a common basis which he has not been able to do in the past.

# Automatic Stations

## ANNUAL REPORT OF COMMITTEE ON AUTOMATIC STATIONS*

### INTRODUCTION

THE Committee on Automatic Stations was appointed by the Board of Directors, April 8, 1927. This, its first annual report, will give a general description of automatic station development during the past decade, and will enlarge upon some of the more important new features brought forward during the past year. Research, operation, standards, bibliography, and suggestions for future study will each receive attention.

### SCOPE

Broadly, the scope of work is comprised under automatic generating stations; automatic substations; and automatic station auxiliaries and the committee has complete jurisdiction over the apparatus that is associated with such installations and in the building or enclosing housings. Successful installations demand proper ventilation, temperature and moisture surveys, and with these, in addition to the various auxiliary apparatus associated with the control, the committee is concerned.

### RESEARCH

Research has been carried forward by operating and manufacturing companies with assistance rendered by several universities. The principal studies have been concerned with the operating requirements of devices for various classes of service. The number of cycles of operation per year for some of the more important devices has been determined.

Overcurrent relays, differential relays and other similar protective relays operate through about 300 or less cycles per year. Overcurrent circuit breakers in railway service may operate through as many as 1000 cycles per year. Load-limiting resistors may be introduced into circuits by the operation of their short-circuiting devices from 500 times per year in Edison Service to 100,000 or more times per year in interurban railway service. Regulating relays may be called upon to operate between 1,000,000 and 30,000,000 cycles per year. Other devices may be called upon to operate between the limits as given for overcurrent relays as an average minimum and regulating relays as an average maximum. Each application, particularly to automatic station service, requires a full knowledge of operating requirements in order to derive a maximum benefit from the particular device in its particular service.

Another field of research has been in the determination of the minimum protection required for various classes of power apparatus in automatic stations. The results of these studies are given in the Standards for Automatic Stations recently approved by the Board of Directors. Still another field for research has been in the study of operating conditions and requirements so that the automatic stations might be designed along simpler lines to give greater reliability and continuity of service. Valuable assistance has been rendered to the manufacturers by the engineers of operating companies. Several papers were prepared and presented by these engineers describing their experiences with automatic stations. This has stimulated the manufacturers toward the development of less complicated devices which give more reliable operation and permit better service to be rendered by public utilities.

### DEVELOPMENT

Development has been directed toward simplifying operating sequence, reducing the number of devices required for various classes of equipment, and making the operation more positive and reliable. Controls have been developed recently for power rectifiers. A brief description of the outstanding features of these designs is given later.

Supervisory systems for the control of remote power apparatus have reached a high state of development. Several papers indicating the trend of this development have been presented to the Institute. Many refinements have been incorporated and these systems are now considered to have an important field of application.

Telemetering is new. Only about a dozen systems including it are in service. Operating experience is needed. The state of development has not yet been passed. Several systems now being offered are simpler and more reliable than the older ones. They indicate that this important adjunct for automatic stations may soon be incorporated in standard designs.

### POWER RECTIFIERS

Power rectifiers are the latest type of power conversion apparatus to be used in automatic stations. These differ from the usual rotating power apparatus in that they have no inherent mechanical moving parts. They differ from the usual static power apparatus in that they require auxiliary features which have mechanical moving parts.

The power rectifier employing mercury is a static converter with a moving arc stream. The load responsive starting and stopping features of the control resemble those used for rotating synchronous converters. The methods used for starting and for stopping, and the protective measures resemble those used with static transformers having artificial cooling. Several features, however, are peculiar to the power rectifier. They are: (1) the rectifier must be ignited and (2) a relatively high vacuum must be maintained.

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Ignition of the rectifier is accomplished by a moving auxiliary electrode. Some schemes use alternating current for the arc starting. Some use direct current. When alternating current is used for ignition, two additional auxiliary starting electrodes are required. The ignition equipment is fully automatic. It starts the arc as soon as a-c. power is available. It extinguishes the starting arc as soon as the power arc is formed and maintained. It will re-ignite the rectifier automatically if for any reason the power arc is extinguished.

The required vacuum is usually maintained by two pumps. One is a rotary motor driven oil sealed mechanical pump; the other a mercury condensation pump. These start and stop in response to vacuum conditions as indicated by a vacuum relay.

Water cooling systems are usually favored for preventing the rectifier temperature rising above a specified maximum. It is controlled by conventional thermal relays connected in the operating sequence of the automatic switching equipment.

The minimum protection recommended for power rectifiers is less than that recommended for synchronous motor generators and synchronous converters, but is greater than that recommended for static transformers, synchronous hydroelectric generators, and synchronous condensers.

Protection against a-c. undervoltage, single-phase starting, and single-phase operation is sometimes required for power rectifier auxiliaries under certain conditions. Protection against severe a-c. over-current is generally required. It may be self-resetting in the case of power rectifiers, while it is usually of the lock-out type for rotating machines. This is due to the difference in the inherent characteristics of the two machines. Protection against d-c. reverse current and excess temperature due to sustained overload is provided for the power rectifiers just as for rotating power apparatus. Power rectifiers, unlike most other types of power apparatus, are usually provided with protection against poor vacuum, failure of vacuum pump, and failure of cooling fluid supply.

The starting and stopping of power rectifiers in automatic stations follows the same principles as developed for rotating machines. Some device substitutions are made in the protective circuit to suit the individual characteristics of the rectifiers. Similarly, load-limiting and load-shifting features may be provided just as for rotating machines, particularly synchronous converters.

In general the automatic control for power rectifiers is similar to that for rotating machines, excepting where it has been necessary to develop some special devices to suit the peculiar characteristics of the rectifiers just as it was necessary to develop special devices for some of the peculiar characteristics of synchronous motors, d-c. generators, synchronous converters, and other types of power apparatus.

### SUPERVISORY EQUIPMENT

Supervisory equipment is rapidly assuming an important place in the design of electric power systems. It is being used not only for the supervision of automatic stations, but for the supervision of important power distribution networks and the operation of large substations and generating stations. The trend is definitely toward a simple system normally at rest. Any operation either to actuate a device or to report an actuation starts a sequence. This usually continues until the operation and report are completed. Then the system remains at, or returns to, a position of rest.

Three or four line wires continue as standard for supervisory systems with visual indication of operation and the usual operating currents and frequency. Carrier-current systems use either one or two wires, or, in some cases, are superimposed on power circuits. Each method has a field of application depending upon local conditions and operating requirements.

Several designs of supervisory equipment use the ordinary telephone apparatus and telephone communication circuit for both talking and control, as well as answer back. These have a relatively restricted application.

Reliability of supervisory systems and equipment is only as good as the line wires which are provided. The terminal apparatus may be perfect. It may operate precisely as the designer intended it to operate. Yet, if the wires connecting the terminal equipments fail, the entire system is rendered inoperative. It is necessary that this feature of supervisory equipment be taken into account in its application, since it has shown a definite limit for such systems under present day operating conditions.

### TELEMETERING

Telemetering is just coming to be recognized as a distinct necessity in the operation of automatic stations, particularly those forming part of large electricity supply systems. Developments have been rapid during the past two years. A number of systems is on trial, most of them too elaborate for economical application. Some give promise of meeting the requirements of high accuracy, low cost, reliable operation, and freedom from resistance and other circuit errors.

The telemetering systems now in operation are used for a very wide variety of purposes. Some give readings of circuit current and voltages. Some give readings of station load. Still others are used for transmitting to a central office, the readings of total station loads, and also for again totalizing all the stations on a system and returning this total to each of the contributing stations.

Still other systems are used for giving a central dispatcher knowledge of the distribution of demand over a given system. Others serve to adjust the supply of power from two sources in proportion to the load demand required from these two sources.

In another year, operating experience should be available which will permit a better picture of the trend of this very interesting development to be given more definitely.

### CARRIER CURRENT

Carrier currents in frequencies from 500 cycles to over 50,000 cycles are being used for the operation of supervisory and telemetering systems. Some of these are used in combination with automatic stations. Some are used for the operation of power apparatus in remote stations. Several papers have been presented to the Institute on this subject and the discussion of these papers gives the trend of thought. A great deal of research and development work is being done on this subject and future reports will no doubt be able to give more comprehensive data concerning it.

### OPERATING EXPERIENCE

Operating experience, particularly that with automatic stations, has formed the subject of several papers presented before the Institute. The art would advance very much more rapidly and more surely if more operating engineers would take it upon themselves to present to the membership, through papers read at regional meetings, their individual experiences with automatic stations. The manufacturers and designers recognize that each power system has its individual characteristics. These require the fitting of automatic stations, individually to each power system. Notwithstanding these facts, all systems have a certain similarity. They also have certain operating requirements. The art is handicapped because the designers do not obtain freely from the operators the system requirements and performance under given conditions. A number of the operating engineers have contributed richly toward the development of the art by telling of their experiences. It is believed that a broadening of this idea will do much to stabilize the industry.

### MAINTENANCE AND INSPECTION

Maintenance and inspection of automatic stations are prime requisites for their successful operation. To obtain a maximum benefit from these stations it is necessary that they be given adequate, systematic, and intelligent inspection. The word "intelligent" really covers the field, for, in a broad sense, it includes the words "adequate" and "systematic."

Much of the development work carried on by the manufacturers has been with the idea of reducing the necessity for maintenance and inspection to a minimum. The devices and schemes of operation which have been produced from this development render the automatic station a unit in any system, which not only contributes to the economic operation of that system, but which also does much to promote continuity of the service supplied by that system.

Practical analysis verifies the statement that "Nothing is perfect." Any commercial device is a compromise between perfection and cost. The quality of service to be expected is thus necessarily a measure of the maintenance required to affect those things by which a device or an equipment as a whole fall short of perfection. If the outage of a unit is not a serious matter, time may be allowed for clearing a failure in the switching sequence. This would normally render the unit inoperative under certain conditions; hence there might be a tendency to neglect the matter of routine inspection or maintenance.

In protective devices, however, the failure which might result in costly damage as well as extended outage is a far more serious matter. For this reason, the automatic station is safeguarded by protective devices not ordinarily found in attended stations. In protecting against equipment failure, one protective device is often reenforced by another, so that only by simultaneous failure of separate and independent protective devices can serious damage be done to the equipment. These protective devices are the product of many years of research, development, and experience. It is necessary, however, that they be used intelligently. They must be suitably adjusted and adequately maintained if it be expected that they render the service for which they were intended.

The importance of continuity of service renders the proper functioning of switching sequence of equal importance with that of protective equipment. A knowledge of the proper functioning of each device and its relation to other devices is the first qualification for one responsible for the inspection or maintenance of an automatic station. Such an individual need not be a technically trained man; in fact, often he is not. He should, however, have a thorough grasp of the fundamentals, and have experience not only in the operation of the equipment itself, but in the relation of the station to the rest of the system. The latter is essential if he is to be able to analyze properly the limitations of the equipment and make adjustment of it accordingly.

With each equipment the manufacturers usually supply instruction books and diagrams giving a comprehensive analysis of the scheme of operation, as well as detailed information of each device. If he is to give the station the best attention an inspector, or maintainer, should be thoroughly familiar with the contents of the instruction book and wiring diagram.

Sometimes the maintainer overdoes his job in such matters as cleaning and filing of contacts. Relays are usually under covers. Inspection of the parts is facilitated by the use of glass, making the removal of the covers necessary only at infrequent intervals. The removal of oxide from contacts is accomplished by the use of crocus cloth, or cleaning with carbon tetrachloride. Contacts in the power circuits and the heavier duty control circuits, when properly adjusted, will require little or no dressing of the contacts. They should be kept clean and bright. Filing is usually not required, as the contacts wear naturally to better surfaces than may be effected by filing. Unless carefully done, filing tends to make matters worse, and even shortens the life of the contact.

Judicious lubrication of moving parts, cleanliness, and the keeping of wiring connections and interlock adjustments tight are the principal factors having to do with the proper maintenance and inspection.

The frequency of inspection of any particular station is best determined by those in responsible charge of the systems. The experience of others in the operation of similar equipment in like service may be used as a guide, but seldom serves as a standard to be followed, since operating conditions are never identical. A brief experience with an inspection schedule will determine where it should be modified so as to give best results. An inspection report made in preliminary fashion with mimeograph copies might well be used during the the first few months until a definite plan is decided upon. Samples of inspection report forms used by a number of operating companies are now available and may be had upon request from them.

A summation of the situation is given by a member of the committee who has had a number of years of experience in the operation of automatic stations. He states that several years of experience with daily inspection, not having a definite routine, did not produce the required results. Railroad equipment is operated on a car or locomotive mileage basis as determined by the conditions. It is then taken into the shop, thoroughly overhauled and sent out on the road subject to a trip of casual inspection somewhere on the road, until it has operated a certain mileage. Then it is returned again to the shop for general inspection. It is logically assumed that after such an inspection, it should cover a predetermined number of miles without attention. The same assumption can be accepted for the inspection of automatic station equipment. There should be a periodic thorough inspection; weekly on some parts of the equipment and monthly, semi-annually, or annually on other parts. Rotating equipment may have to be cleaned at intervals of two or three days,—or even longer,—depending upon the number of hours run and conditions of ventilation of the station. The station may have to be visited daily for other reasons than inspection of apparatus where no supervisory equipment is used. With supervisory control, no other attention should be needed than cleaning and periodical inspection.

### STANDARDS

A final report on Standards for Automatic Station No. 26 was presented to the Standards Committee at its January 20, 1928 meeting. Following a letter ballot, this report was submitted by the Standards Committee to the Board of Directors with the recommendation that it be approved as an A. I. E. E. Standard. The Board of Directors approved the Standards for Automatic Stations, April 6, 1928.

The Committee on Automatic Stations intends to present revisions of these standards to the Standards Committee from time to time as the necessity for them may arise.

### FUNCTIONAL NUMBERS

Functional numbers have been used for automatic station devices and functions for about 15 years. A gradual standardization has resulted. The latest list is given in the Standards for Automatic Stations recently adopted by the Board of Directors.

The functional numbers initially followed the sequence of operation of the devices. Later, as automatic stations developed, this sequential numbering could not be followed. It resulted in an arbitrary numbering system which has become generally known in the art.

The present numbering system uses a base of not more than two digits. The numbers from 1 to 99 inclusive cover the entire range of basic functions. Numbers in the 100, 200 and other series are used for designating these functions when used with feeders, supervisory systems and the like. The system of numbering the functions, however, still remains arbitrary.

It has been thought that a system of numbering more logical and less arbitrary might be developed. A subcommittee has had this matter under consideration since December 1, 1927. They have rendered several reports. Progress has been made, but a solution has not yet been supplied. It is recommended that a subcommittee be appointed to continue the study of this important topic during the ensuing term.

### PAPERS

Papers presented under the auspices of, or in cooperation with, the Committee on Automatic Stations during the current year have been as follows:

| Subject | Author | Place & Date |
|---|---|---|
| Operation and Performance of Mercury Arc Rectifiers. | Caesar Antoniono | Chicago–Nov. 1927 |
| Automatic Control of Edison Systems................ | O. J. Rotty & E. L. Hough | New York–Feb. 1928 |
| Automatic Switching of Incoming Lines and Transformers.................. | A. E. Anderson | St. Louis–March 1928 |
| Mercury Arc Rectifier Substations................. | G. E. Wood | New Haven–May 1928 |

### UNFINISHED BUSINESS

Topics which have been under consideration by the committee and concerning which no report has been rendered are as follows: (1) Ventilation; (2) Fire protection; (3) Economical construction; (4) Unusual operation conditions; (5) Load dispatching; and (6) Wire designations.

In addition to these items of unfinished business, there are other items upon which reports have been rendered but which do not fully close the subject. These are as follows:

(1) Papers, (2) Standards, (3) Research, (4) Operation reports, (5) Remote metering, (6) Supervisory control, (7) Progress in the art, (8) Inspection, (9) Functional numbers, and (10) Bibliography.

It is recommended that these subjects be given consideration by the succeeding committee.

### BIBLIOGRAPHY

Many requests have been received from time to time for a bibliography on automatic station literature. Such a bibliography has been prepared and forms an appendix to this report. It is recommended that future committees add to this bibliography so that there may be found available in the TRANSACTIONS of the Institute a comprehensive bibliography on the subject.

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# General Power Applications

## ANNUAL REPORT OF COMMITTEE ON GENERAL POWER APPLICATIONS[*]

*To the Board of Directors:*

Your Committee on General Power Applications endeavored to perform the following functions:

1. Keep in touch with all developments relating to general power applications.

2. Foresee the need for development of new electrical apparatus to meet new conditions in general power applications.

3. Develop papers to be presented before the Institute on subjects relating to general power application.

4. Present a report at the end of the Institute year recording the development of general power applications during the preceding year.

To accomplish the first function, a review of the technical press was undertaken, each committee member being asked to review certain periodicals. To be successful, a review of this type requires the sacrifice of considerable time from our daily occupations and is not extremely fruitful in results even if such review is punctiliously observed. However, we were fairly successful in this endeavor.

The second endeavor mentioned above is the hardest of all to attain but is one which, if successful, would add much to the value of the committee.

The third endeavor has brought out many suggestions for prospective papers. These include the following:

High Cycle Equipment for Portable Tools.
Telephone Central Office Power Plants.
Short Circuit Protection for Industrial Installations.
Overload and Single Phase Protection for Across-the-Line Squirrel-Cage Induction Motors.
Application of Power and Control Equipment to Power Plant Auxiliaries.
Across-the-Line Starting of Induction and Synchronous Motors, Including 2200 Volt Application.
Improvement of Ward Leonard Control with Special Reference to Application to Elevators.
Mass Production of Electric Light Bulbs.
Storage Batteries, Improvements and Applications.

Instead of enumerating a large number of new applications, only representative ones are cited in this report. Details of these are more specific than formerly and we feel that in drawing these to the attention of the membership, we shall have focused their attention on the general trend of all applications. Necessarily, there are many types not mentioned, either because the committee has no access to such, or because their application is somewhat similar to others.

The thanks of the committee is extended to the Allis-Chalmers Mfg. Co., American Telephone & Telegraph Co., Bethlehem Steel Co., D. H. Braymer Equipment Co., Canadian General Electric Co., Century Electric Co., Consolidated Gas, Elec. Lt. & Power Co. of Baltimore, Cutler-Hammer Mfg. Co., Duquesne Light Co., Edward Ford Plate Glass Co., Electro-Dynamic Co., General Electric Co., Graybar Electric Co., Howell Electric Motor Co., Lincoln Electric Co., Louis-Allis Co., The Management Engineering & Development Co., Ohio Bell Telephone Co., Philadelphia Electric Co., Reliance Electric & Engineering Co., Stone & Webster, Westinghouse Electric & Mfg. Co., J. D. White Engineering Co., the Universities of Missouri, Massachusetts Institute of Technology, Purdue and Toronto, firms with which committeemen are connected or whose cooperation and publications we have made use of in compiling this report.

### MARINE EQUIPMENT

At the close of the year 1927, there had been placed in commission, or were under construction, a total of 118 electrically propelled vessels of various types, ranging from river towboats and small yachts to the largest types of sea-going ships. The equipment of these crafts aggregated more than 700,000 shaft hp., about 92 per cent of the primary power being supplied by turbines and 8 per cent by Diesel engines.

The outstanding event of the year was the completion and installation of turbine-electric propelling equipment for the Panama Pacific Liner *California*, Fig. 1, the largest passenger ship ever built in the United States and the largest electrically driven ship of her class in the world. The *California* is a twin-screw ship with a displacement of 30,250 tons at load draft.

The maximum energy delivered to her propeller shaft is 17,000 shaft hp. and a speed of 18 knots can be maintained with this power input. At the cruising speed of 16.5 knots, the output of the turbo generator is 13,500 shaft hp. and at this speed the ship has a cruising radius of 15,400 mi.

The propelling equipment comprises two 16 stage steam-turbo generators, each having a maximum capacity of 6600 kw. at 2880 rev. per min. This power is transmitted to the propeller shafts by means of two synchronous induction type motors having a continuous maximum rating of 8500 shaft hp. at 120 rev. per min. These motors are direct connected to

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*Presented at the Summer Convention of the A. I. E. E., at Denver, Colo., June 25-29, 1928.*

the propeller shafts and are reversible so that no reversing turbines are required. Both propelling motors can be operated at about ¾ of their rated output by the current supplied from one of the two turbo generators, thus insuring economical cruising at reduced speed.

The *California* was launched October 1, 1927 and work on a second ship of the same size, to be provided with electric propelling equipment of the same power, is already under way.

*Diesel Electric.* While the primary power supplied by Diesel engines is comparatively small compared to that supplied by steam turbines, yet there have been a number of notable applications of Diesel-Electric Drive for marine work.

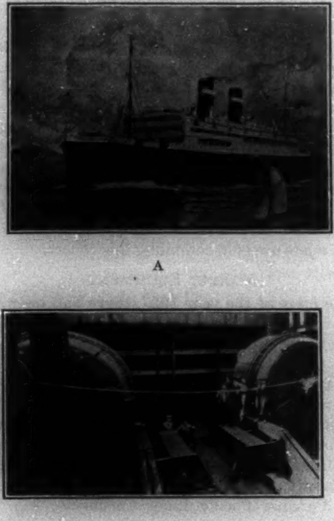

FIG. 1—A. TURBINE-ELECTRIC-PROPELLED LINER *S. S. California*

B. VIEW SHOWING THE INSTALLATION OF THE MAIN PROPULSION MOTORS

One of these in which d-c. apparatus is used is the Coast Guard Cutter *Northland* which is now serving on patrol in Alaskan waters.

The main engine room equipment consists of two Diesel engine-driven generators, each rated 410 kw. 250 volts at 200 rev. per min. These supply current to a double-unit type, shunt-wound propeller motor, Each section of this motor (Fig. 2) is rated 500 hp. at 120 rev. per min. The ship will develop a speed of 12 knots with her single propeller operating at 120 rev. per min. and the motor developing 1000 shaft hp. The control is located in the engine room and is of the variable voltage type.

There are some unusual features in the propelling equipment, one of them being the use of a magnetic clutch between the motor and the propeller shaft. Under normal conditions the motor and shaft are rigidly bolted together, but when cruising at reduced speed in the ice fields the bolts will be removed and the power transmitted through the magnetic clutch. This will transmit a torque equivalent to 500 shaft hp. at 95 rev. per min., but any increase of load beyond this rating will cause the clutch to slip and will thus prevent dangerous stresses.

Other applications of Diesel-Electric Drive include that on four large double-end Diesel-electric ferry boats made for the Southern Pacific Company for service in San Francisco Bay, electrically propelled packet boats running between points in and around New York Harbor and cargo boats recently open to Diesel electric propulsion by the U. S. Shipping Board. Another novel application of Diesel-electric drive was inaugurated by the Bureau of Light Houses by its decision to adopt this method of propulsion for three new light ships. These ships are at anchor most of the time but in severe weather, the propulsion equipment will be used to take the strain off the anchor chains and to maintain the position of the light in the event of the breaking of the moorings.

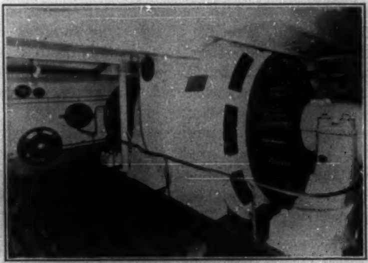

FIG. 2—U. S. COAST GUARD CUTTER *Northland's* 1000-HP., 120-REV. PER MIN., 500-VOLT DOUBLE ARMATURE PROPELLER MOTOR

*U. S. Navy.* The Washington Arms Conference in 1921 served to greatly emphasize the consideration of the relative value of weight and space for power apparatus on board ships. Recent designs of machinery have shown a marked advance over previous practise in the matter of lightness and compactness without sacrifice of strength or reliability. This has been made possible by the use of light metal alloys and the use of fabricated steel parts to replace the original cast iron parts. Cast iron is not only too heavy a construction, but is also unreliable under such shocks as are imposed by battle conditions. The chief developments in application in the past year have been along the lines of building machines to meet the peculiar needs of the application.

A notable application is that of a 200-hp., 5000-rev. per min. d-c. motor on which the Navy Department has recently completed tests. This motor is used to drive a three-phase blower type compressor having a capacity of 3200 cu. ft. and a discharge pressure of 10 lb. Special precautions had to be taken to balance this armature, the peripheral speed of which is approximately 20,000 ft. per min. The bearings are flood-lubricated, the oil being supplied by a separate motor-driven pump. The method of cooling is novel, the cooling air being that which is drawn through the motor into the first stage of the compressor.

## ELECTRIC RAILWAYS

The applications in the electric railway field were concentrated mainly upon the modernization of rolling stock. Existing cars were replaced with equipment better suited to modern transportation requirements, including motors and control of the latest design.

*Oil-Electric Locomotives.* Interest in the application of oil-electric locomotives continued throughout the year and a number has been put in service. These demonstrate the economies and other operating advantages of this type of drive. Two 100-ton units are now in heavy switching service on the Erie Railroad and 60 ton units were completed for the Chicago & Northwestern Railway, the Union Carbide Company, and the American Rolling Mills Company. Work is also proceeding on oil-electric, freight and passenger locomotives for the Putnam Division of the New York Central Railroad and a 300-hp. oil-electric motor car is ready for service.

*Gas-Electric Motor Cars.* One of the large automotive truck manufacturing concerns has recently announced the completion of car units consisting of gasoline engines and electric generators, to be used with an electric drive to furnish power for virtually any kind of transportation. This is unique in that a single base contains all the power equipment and accessories except the gasoline tank, the radiators and such electric motors as may be used in driving the axles. An important application is expected to be railway transportation. More than one power unit can be used, ranging from a single day coach moving along the rails without the help of a locomotive, to a six-car commuter train in which the cars at each end of the train contain power units. By means of a system of remote control, these units can be operated by an engineer at either end of the train.

*Special Type Locomotives.* A new combination trolley and storage battery type of locomotive has recently been placed in service by the Chicago, North Shore and Milwaukee R. R. These locomotives may be used either on the trolley system, or on tracks not now equipped with trolleys. The motors are ventilated by electrically driven fans. D-c. control is provided for either trolley or battery and transfer from the trolley to the battery power is automatic. Motor-generator sets are used for charging the battery when running from the trolley.

*Automatic Substations for Railway Signaling Power Supply.* The continuous inductive type of automatic train control provides a new field for the application of small frequency-changing motor-generator sets and automatic control for starting the sets and for connecting the generators to the load in the shortest time possible. Power is supplied to the train control system at a frequency of 100 cycles in order to eliminate inductive interference from commercial circuits.

Motor-generator sets provide the 100-cycle power from 25 or 60 cycle primary sources. The motor-generator sets range in size from 1.5 kv-a. to 60 kv-a. The rating depends primarily upon whether the power is to be used for both automatic train control and automatic block signaling or only for the former.

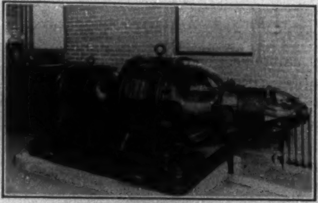

FIG. 3—MOTOR GENERATOR SET

A very interesting installation of automatic substations to provide 100-cycle current for the operation of both automatic block signaling and automatic train control is on the Pan Handle Division of the Pennsylvania R. R. system between Pittsburgh, Pa. and Newark, Ohio. This division consists of 158 route mi. or 375 track mi. Eight automatic substations are provided, the maximum distance between any two adjacent stations being 36 mi. and the minimum five miles. Each station, excepting one, contains a 60-kv-a. 80 per cent power factor, 220-volt, single-phase, 100-cycle alternator, with direct connected exciter, driven by a direct connected 75-hp., 220-volt, three-phase, 60-cycle, squirrel-cage induction motor with the necessary automatic switchgear. Fig. 3 shows one of the seven motor-generator sets and Fig. 4 shows one of the automatic switchboards. The motor starter is in the foreground, next are two feeder panels, one to feed east and the other to west. Next is the relay panel followed by the voltage regulator panel. The panel in the background is for the control of the two motor-driven air compressors in the extreme background and is not part of the automatic switchgear.

## MINING INDUSTRY

A new type "sealed equipment" cable-reel-gathering locomotive has been provided for mine application and is provided with two 30-hp. motors, contactor control of the progressive series parallel type, and a motor-driven cable reel with 450 ft. of double-conductor, concentric, rubber-covered cable.

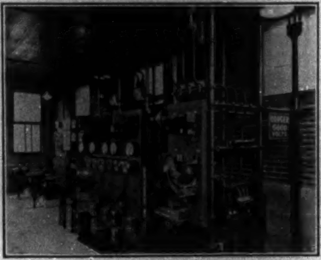

FIG. 4—AUTOMATIC SWITCHBOARD

The traction motors, the cable-reel motor, cable-reel collector rings, control, headlights, and all parts of the equipment with the exception of the trolley pole and the reel cable are completely enclosed in strong cases which are designed to prevent any gas explosions that occur within these cases being transmitted to the surrounding atmosphere. With the exception of short sections of cable leading to the motor, where flexibility is necessary, all wiring is enclosed in rigid type conduit, securely anchored and provided with steel fittings where it enters the various compartments. Flexible motor cables are enclosed in heavy rubber hose, the ends of which are also provided with steel fittings; Figs. 5 and 6 show views of this type of locomotive.

FIG. 5—ELECTRIC MINE LOCOMOTIVE

*Quarry Locomotive Cars.* An interesting system of remote control for locomotive cars operating on quarry tracks was developed. With this system a single operator, located in the tower-control station, from which he can see all the cars, is able to start, stop, and even to switch cars on different tracks. Electrical equipment of the cars consists of high-torque squirrel-cage motors provided with solenoid brakes and controlled through a pair of reversing contactors which throw the motors on the line at full voltage. Two current-collecting shoes are used for making contact with two "third rails" located between the traction rails. The separate tracks on which these cars operate have isolated circuits or the cars can be maneuvered on a loop track with isolated sections.

FIG. 6—INTERIOR VIEW

The control operator handles the cars from a pilot switch which actuates the reversing contactors and, when the current is shut off, the solenoid brakes set automatically and retard the car, torque being adjusted for smooth retardation. The application of this system is expected to speed up production and reduce operating cost, inasmuch as one operator can in this way handle several cars whereas with the old system an operator was required for each car.

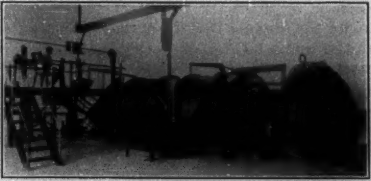

FIG. 7—3200-HP., 79 REV. PER MIN. D-C. HOIST MOTOR

*Largest Hoist Motor in Western Hemisphere.* We are continually having our attention called to the ever increasing size of electrical equipment being used in the industries. One of the large electrical manufacturing companies is building for the Frood Mines of the International Nickel Company of Canada a 3200-hp., 79 rev. per min. d-c. hoist motor. On both the horsepower and torque rating, this motor is larger than any single mine hoist motor yet installed or selected for mine hoist applications in this hemisphere. Fig. 7 illustrates this motor.

Its armature will be 144 in. in diameter and power for the motor will be supplied by a fly-wheel motor-generator set consisting of a single a-c. motor driving two 1250-kw., 600-volt generators. The hoist has cylindrical drums 12 ft. in diameter and is of the balanced skip type for the handling of ore from a maximum depth of 3000 ft. The load will vary with the depth and at 2000 ft. the skip will handle 10 tons of ore at a speed of 3000 ft. per min.

This equipment will employ the variable voltage d-c. system of speed control.

*Improved Equipment for Gaseous Mines.* In gaseous coal mines an explosion of gas may occur, this explosion be communicated to the fine coal dust deposited on the sides, roof and bottom of the mines, thus extending and materially augmenting the initial explosion and, perchance, causing a disaster of large proportions. In order to prevent the gas explosion communicating with the coal dust, the latter is covered with rock dust which is distributed to the walls, roof, and bottom of the mine under air pressure. Fig. 8 shows a machine used for this purpose. The rock dust is contained in the hopper at one end of the machine and is distributed by the motor-driven blower. This equipment is capable of delivering the rock dust through several hundred feet of hose to entries on either side of the track. The blower delivers a constant volume of air at a fixed velocity regardless of the length of hose.

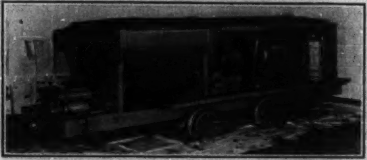

Fig. 8—Machine for Distributing Rock Dust

The electrical equipment is especially designed for use in gaseous mines and has been approved by the Bureau of Mines for this application. It consists of a 20-hp. permissible type motor and control. The motor has solid rear brackets and bronze screw type inspection covers on the commutator end. The controller is of the full magnetic push button type. The contactors, overload relay, starting resistor, and push button are all enclosed in a single case arranged for easy inspection of the equipment.

By using the packing gland type of lead entrance the electric cables can be run without external connection from the inside of the motor to the inside of the controller. The design results in a very simple method of mounting and wiring the electrical apparatus. The push buttons which are enclosed in the case are operated by two plungers extended through the case and protected by a housing cast integral with the top of the control.

*The Largest Mine Locomotive.* The largest single unit underground mine locomotive was exhibited at the American Mining Congress Convention in May. This locomotive weighs 38 tons and has the following limiting dimensions: Gage 35 in., height 46 in., width 64½ in., overall length 24 ft.-0 in. The locomotive is equipped with three 133-hp., 500-volt motors or a total of 399 hp. per locomotive. The motors are arranged for forced ventilation from a separate blower motor. The control is of the semi-magnetic type, series-parallel with overload relay and no-voltage protection.

The locomotive was designed for a haul of approximately four miles with an average grade of approximately 2.4 per cent and a maximum grade of 5.6 per cent for a thousand feet and will haul an average of 50 cars per trip and make 9 trips in 8 to 8½ hr. The car weight loaded is approximately 3½ tons average. Fig. 9 illustrates the locomotive.

## GLASS INDUSTRY

The application of motor drive in the glass industry is of course not new. The excessive demand of thin plate glass of the non-shattering type, and for ordinary thin plate, such as used in the auto and allied industries, has caused a general building and rebuilding program for this type of glass manufacturing.

The use of electrically driven mechanisms at practically every step and the fine instruments required as well as powerful cranes, etc., has created a great and growing demand for motors, controllers, and general equipment to improve the methods of manufacture of thin plate glass.

Fig. 9—Largest Mine Locomotive

## ELECTRICAL REFRIGERATION

The enormous growth of motor application in the field of electrical refrigeration is indicated by the fact that ten years ago this industry produced about 1200 units a year, whereas the year 1927 produced 1,500,000 units.

The introduction of the electrical refrigerator into the home has added during 1927 a revenue of $3,000,000 to the Power Companies' earnings.

An interesting application in this field is the use of single-phase motors mounted in rubber. All single-phase motors have an inherent double frequency torque pulsation which gives rise to some noise and vibration. Fig. 10 shows a 1/30 hp. split-phase motor of the usual construction but with this unusual mounting.

The base of the mounting has vertical supports going up through the ventilating holes in the bottom of the end-flanges of the motor and offset around the shaft so that the top of the support is directly over the shaft and some distance above it. There are two holes in each support, one above and one below the shaft with rubber bushings in these holes. Two pins extending inward from the end-flange engage these rubber bushed holes and support the motor. The motor is thus supported entirely from these pins in the end-flange and there are no metal-to-metal contacts between the motor and its mounting. This rubber mounting has two advantages over a rigid mounting in that it eliminates a large part of the vibration normally transmitted to the apparatus on which the motor is mounted and it also reduces the usual motor noise to a minimum, as the motor can produce noise only by vibration in the relatively small surface of its own frame.

In this field also, it is interesting to note the application of what is essentially a two-phase motor from a single-phase line, one phase of the motor being connected directly across the source of supply and the other phase connected in parallel with the first phase through a capacitor. In order to secure best operation, it has been found desirable to make a change in connections on the capacitor as the motor comes up to speed. This change is made by the use of a single centrifugal device which operates a single-pole double-throw switch. Due to the fact that it has no commutator or brushes, it is extremely quiet and causes no radio interference except one slight click when the centrifugal switch operates. The fact that the motor operates as a polyphase motor has a tendency to eliminate the characteristic hum of a true single-phase motor.

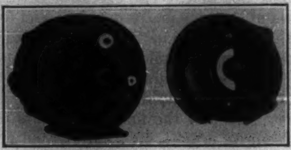

Fig. 10—Split-Phase Motor Frame with Cushion Base

### Paper Mill Industry

A new application in the manufacture of paper is that of an adjustable speed motor to a paper winder. This drive consists of a direct connected variable speed motor and the necessary control equipment. The motor is designed to give a speed range of 4 to 1 by voltage control and to give a crawling speed for threading the paper by means of armature resistance. This particular drive was supplied at the mill of the Fraser Co., Ltd. at Madawaska, Maine, and has caused a great deal of favorable comment because it is an economical arrangement when viewed from the standpoint of first cost and has proved a very satisfactory arrangement from an operating standpoint, all the features having been combined in it which are ordinarily secured only through a Ward Leonard system of speed variation.

### Electric Furnaces

For a number of years the wrought brass industry, concentrated in a comparatively few large plants, has used electric arc and induction furnaces almost exclusively for melting copper-zinc alloys. The cast brass industry, consisting of many small plants widely scattered, has been slower in the adoption of electric heat for melting but there was an increased use of electric furnaces for melting brass for castings. The brass industry as a whole uses comparatively small melting units, 75 to 200 kv-a., all single phase. There appears to be less objection than formerly on the part of public utility systems to single-phase loads of this character, and units as large as 300 kv-a. have been installed.

In the steel industry the use of the three-phase arc furnace of the three-electrode type followed the standard practise of the last two or three years and "electric steel" has now become a trademark to indicate a superior quality of steel.

There is a decided growth of interest in the possibilities of cast iron of uniform analysis and of definite physical properties. This is one of the most promising applications of the electric melting furnace.

The coreless type induction furnace, generally referred to as the "high-frequency furnace," entered the ferrous field for the production of high grade alloy steels. Completed equipment of this character included a 150-kv-a., 900-volt, 2000-cycle unit for melting steel, 1 60-kv-a., 900-volt, 960-cycle unit installed for laboratory service in a large steel plant, and a 187-kv-a., 900-volt, 800-cycle unit shipped to Sweden. All of these units consist of a motor-generator set, using a three-phase motor of standard frequency and voltage to drive a single-phase high-frequency generator, together with the corresponding high-frequency capacitor units.

In the December 16 number of the *Electrical Review*, London, there is an article on a high-frequency steel furnace, this furnace being operated by a 150-kw. motor-generator set and used for only the very finest steel. This appears to be another application of electricity which betters the product and does away with a great deal of hard exacting labor, inasmuch as it is the first radical departure from the primitive coke furnace for making crucible steel. This furnace is in operation at the Imperial Works of Messrs. Edgar Allen & Co., Sheffield, England.

### Steel Mill Industry

*Automatic Steel Mill.* A great improvement in the rolling of steel was inaugurated during 1927 which has made it possible to roll the "H" shaped beam so desirable for columns in buildings. The improvement consists in using sets of rolls to roll simultaneously the flanges and web of the beam. The adjustments of all of the rolls is made automatically at the same time. Important new features were also developed for the motor driving these rolls.

Fig. 11 shows the main motor room for the new mills at the Homestead plant of the Carnegie Steel Company which roll these "H" section beams. The total capacity of the electrical equipment in this one room is nearly 85,000 hp., thus making it one of the largest industrial substations yet installed.

In the right center and extreme back part of the motor room are shown the reversing motors which drive the mill rolls of the roughing and intermediate 52-in. universal beam mills. Each of these mills has three pairs of rolls, all working simultaneously on various parts of the same beam section. The main horizontal and vertical rolls are driven by a 7000-hp. motor, and the horizontal edging rolls are driven by a 200-hp. motor, both of these reversing motors being supplied with power from a 6000-kw. flywheel motor-generator set.

Fig. 11—Main Motor Room, Carnegie Steel Company

Automatic control is provided, which permits a single operator to control the operation of the two motors, the three screwdown motors, and the several table conveyor and transfer motors. By means of a plug-in board, the ratio of the speeds of the two reversing roll motors is predetermined and selected for each pass, and the screwdown setting of each set of rolls is selected for each pass. During operation, the operator then advances a multi-point master switch one position after each pass, and the control functions automatically to adjust the ratio of roll motor speeds and to set each of the sets of rolls, ready for the next pass.

By this method of control, the operation of the mill is very greatly simplified, the number of operators is reduced, and the product is of uniform quality due to the same processing of succeeding pieces.

*Mill for Wide Flanged Beams.* Another large equipment of unusual interest was placed in operation at the Lackawanna Plant of the Bethlehem Steel Company. The mill to which the motors were applied is used to produce wide flange beams. It consists of three units; a 54-in. reversing blooming mill, a 48-in. intermediate mill, and a 48-in. finishing mill. The blooming mill, which is one of the two largest reversing blooming mills in this country, is driven by a single-unit d-c. reversing motor rated 7000 hp., continuously at 50 deg. cent. rise and 40/80 rev. per min. This motor is capable of exerting a maximum torque of 2,400,000 lb. at one ft. radius. Direct current is supplied from a flywheel, motor-generator consisting of a 5000-hp., 375 rev. per min., 6600-volt induction motor, a 50-ton flywheel and two 3000 kw., 750 volt generators which are operated in parallel.

Another noteworthy application at the Lackawanna Plant of the Bethlehem Steel Company is the change of the layout of the rail mill which is now being made. The 44-in. reversing blooming mill will have a driving motor rated 7000 hp. continuously, 50 deg. rise and 50/120 rev. per min. Blooms from this mill will go to a 35-in. reversing roughing mill which will be driven by a d-c. motor rated 5000 hp. continuously at 50 deg. cent. and 50/120 rev. per min. Power for these two reversing motors will be obtained from a single flywheel motor-generator consisting of a 7000-hp., 375 rev. per min., 6600-volt induction motor, two 3000 kw., 375-rev. per min., 750-volt generators operating in parallel to supply power to the 7000-hp. blooming mill motor, two 2200 kw., 450-volt generators operating in series to supply power to the 5000-hp. roughing mill motor and a 75-ton flywheel.

*Use of Synchronous Motors in Steel Mills.* The increase in the use of synchronous motors for main roll drives in the past year is noteworthy. The new applications for the year include a 5000-hp., 40 deg., 1000-rev. per min., 2200-volt motor used to drive a 19-in. continuous sheet bar mill at the Kokomo Plant, Indiana, of the Continental Steel Corporation. A motor of the same horsepower rating but at 240 rev. per min. will be used to drive a 51-in. piercing mill installed by the Standard Seamless Tube Co. of Economy, Pa. Other motors are applied to copper and brass rolling mills.

*Motor Rollers.* The first applications of rollers of the type in which the driving motor is inside of the roller and made integral with it were made in the past year. These applications include motor rollers on four different parts of a continuous sheet mill at the plant of the American Sheet & Tin Plate Co., Gary, Indiana. These rollers are of different capacities and speeds, depending upon their location in the table and vary from 5 to 35 cycles per sec. They are operated through motor-generator sets consisting of alternators and adjustable speed d-c. motors to give the necessary speed variation over the different parts of the table.

Another application of these rollers is that at the Lorain Plant of the National Tube Co. Applications here include motor rollers on a runout table for conveying the rounds from the furnace to the piercing mill. Others are used to feed the pipes to and from the threading machines, this installation being entirely automatic, and still others for conveying the tubes through the oiling machines. All of the rollers for the National Tube Co. are made of a special form to accommodate the round stock.

There are many advantages in the use of motor rollers over the geared or coupled type of drive, chief of these being simplicity of mounting with resultant simplicity and cheapening of the table supports, and economy in space and power, and extreme flexibility of operation.

### OIL INDUSTRY

Although electric power was slow to invade the field of oil production, rapid progress has been made during the last two years and now there are many fields using electrical power exclusively. A very good résumé of the operation of an electrically operated oil field is given in the *Electrical World* under date of February 4, 1928.

*Application of Electricity to Pipe Line Pumping.* Recently electric power has been used for pumping oil through pipe lines to replace the slow-speed plunger pumps driven by steam engines or occasionally a Diesel engine, on account of their very high first cost.

During the last two or three years pump manufacturers have made rapid strides in the design of centrifugal pumps suitable for this service and the engineers of the pipe line companies are beginning to realize the advantage of motor-driven centrifugal pumps for this work. Some of these advantages are low first cost, low maintenance, low attendance charges, quickness of installation, and reduced friction head due to steady even pressures. The low first cost (usually one-sixth to one-eighth of the steam station of the same capacity) is of considerable importance in selecting equipment, especially when the life of the field being served is of questionable duration and low fixed charges are prime factors in the total operating costs.

In the summer of 1927 the Illinois Pipe Line Company desired to increase the capacity of their main line across the State of Ohio, from 15,000 bbl. a day to 22,000 bbl. Rather than install additional pipe line capacity at great expense, this company put in booster stations using motor-driven centrifugal pumps at intermediate points between the steam stations. Ten five stage, 650-gal. per min., 1660-ft. head centrifugal pumps driven by 400-hp., 220-volts, three-phase, 60-cycles, 1800-rev. per min., synchronous motors with direct connected exciters were installed in five booster stations, two units per station. Only one pump is required to operate in each station, the second unit acting as a standby. See Figs. 12 and 13. Magnetic pushbutton starters of the auto-transformer type are used throughout, with pressure gages arranged to shut down the motors in case of low or excess pressures. The two pumps, motors, control and auxiliary equipment are mounted in a pump building 24 ft. by 34 ft. A fire wall is placed between the room containing the pump and the room containing the electrical equipment; the motor shaft passes through a stuffing box in the fire wall.

The sucess of these first installations has caused this company to purchase and install 27 additional units of the same kind to operate their new line running from Yates Pool to West Texas to Del Rio. Other companies have also realized the advantages of electric power for this service and have made similar installations so that this method of pumping is rapidly becoming the standard for pipe line service.

FIG. 12—SYNCHRONOUS MOTORS IN BOOSTER STATIONS

### ELECTRICAL WELDING

There was a marked advance in the application of electrical welding during the past year, both for the fabrication of electrical machines of all sizes and for the fabrication of structural beams and pieces necessary in the building industry.

FIG. 13—MOTOR-DRIVEN CENTRIFUGAL PUMP

The use of welded frames is rapidly becoming universal on account of the great saving in weight which can be accomplished by this method. Fig. 14 shows a welded frame for 100,000 kv-a. turbo generator and Fig. 15 shows a fabricated stator frame for one of the 40,000 kv-a. water-wheel generators for Conowingo.

*First Arc Welded Railway Bridge.* The first arc welded bridge of the through girder type is shown

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This bridge spans the power canal passing through Chicopee Falls, which is approximately 50 ft. wide. Owing to the layout of the railroad facilities, however, the bridge is required to cross the canal at an acute angle of 72 deg. As a result the trusses are approximately 135 ft. long and the over-all length of the bridge is approximately 175 ft.

The outstanding feature of interest in the design of the bridge is the fact that the welded design requires 80 tons of steel, whereas the riveted design, prepared by the railroad engineers, required 120 tons of steel. Also the connecting material in the case of the welded bridge runs less than 5 per cent of the weight of the structure whereas in the case of the riveted design the weight of the connecting material is almost 30 per cent of the weight of the total structure.

FIG. 16—ARC WELDED RAILWAY BRIDGE

*Atomic-Hydrogen Arc Welding.* Development work on atomic-hydrogen arc welding was completed and a commercial equipment was produced for use on 60-cycle circuits.

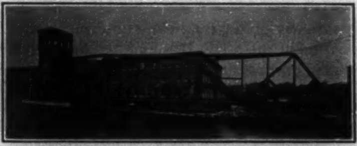

FIG. 17—COMPLETED ARC WELDED THROUGH TRUSS TYPE BRIDGE

With this method of arc welding, an alternating current is maintained between adjustable tungsten wire electrodes, Fig. 18, and hydrogen is fed to the arc around the electrodes. The hydrogen molecules are broken up into atoms by the intense heat and, in recombining outside of the arc and in contact with the work, heat is liberated far in excess of that obtainable by any gas flame alone. This heat is used to fuse the metals to be joined and, where additional metal is required, a filler rod may be fused into the work.

The hydrogen, being an active reducing agent, prevents the formation of oxides and hence produces a uniformly strong, ductile, and smooth weld. The metal being welded is not in the electric circuit and need not be grounded or insulated. The arc, constantly maintained, but broadly adjustable in size and in intensity, lends itself to a wide range of work.

A transformer furnishes the required voltage, and the current at the arc is controlled by an automatic reactor. In this process, high voltage and low currents are required in the arc, which is the reverse of the conditions in ordinary arc welding. The arc is struck at 300 volts; but while welding, the arc voltage is varied from 90 volts for light work to 60 for heavier, and the current correspondingly varies from 20 to 70 amperes.

By this means, homogeneous ductile welds can be made on very thin metals or on some metals and alloys hitherto considered unweldable.

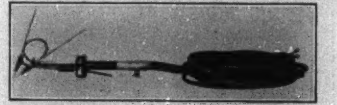

Fig. 18—Atomic Hydrogen Welding Torch

*Magnetically Controlled Arc Welding.* It is claimed by one manufacturer that the superimposing of a strong magnetic field on the arc flame, permits the arc to travel through variable magnetic fields without disturbance. This magnetic control appears to give the arc a gyratory motion and the controlled arc has been called an "electronic-tornado," the magnetic field apparently giving a swirling or gyratory motion to the electrons in the arc. It is claimed that welds made by this new process are more uniform in structure and ductility than those of ordinary arc welding.

Heretofore metal deposited by electric arc welding has partaken of the characteristics of cast steel. By this new process the metal deposited in the weld shows equal or even better physical characteristics than the metal of the plates joined by welding. This is said to be a result of the purifying effect of the electronic tornado.

An article in the January issue of the *Welding Engineer* indicates that a metallurgist who examined micrographs of welds made by this magnetically controlled process states that actually the weld is heat treated steel, and for that reason is entirely free from undesirable hardness and that the refining effect of this new welding process produces weld metal fully as good as that which can be obtained in rolled steel of the same general purity.

### CONTROL

Control has made many developments during the past several years and much was done during 1927. A great many individual devices could be cited indicating the improvements made. The following are given more or less to show the general trend of control. Generally, it should be pointed out that the evolution of dependable definite timing devices has limited the use of current limit and counter e. m. f. schemes of control. The general run of magnetic control is now of the definite time accelerating type.

The year 1927 saw a great deal of development and improvement in thermal overload relays for motor protection and protection for other machinery. The developments during the year are also noteworthy with respect to improvements in magnetic switches. Much has been learned with respect to the characteristics of different metals used as contact breaking and carrying points, also with respect to the advantages of multiple break per pole.

*Automatic Pump Control.* In the automatic control of a pump installation where the centrifugal pump is installed at a higher elevation than the sump, a vacuum pump is usually required for priming the centrifugal pump. The use of a pump valve to keep the pump filled with water so rarely gives satisfactory results in an automatic installation that this method of priming is not often recommended. The use of a sequence drum has made an improvement in automatic pump control. This sequence drum provides the automatic control to start the pump at high water level, stop the pump at low water level, and go through the priming process in starting. It repeats the priming cycle three times if necessary to prime the pump. If the pump is not primed after a third attempt, the sequence drum will lock out the control and a contact will be made on the drum energizing alarm circuit. In case the vacuum breaker switch remains closed, after the pump has primed, the main motor will not be disconnected from the line, but the sequence drum will stop on alarm contact, ringing alarm and lock out starting control, until repairs have been made. The sequence drum is, of course, motor-operated. See Fig. 19.

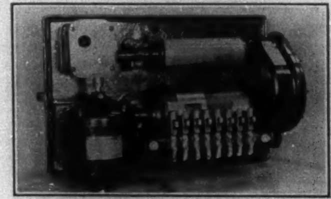

Fig. 19—Motor-Operated Sequence Drum

*High-Pressure Valves.* In connection with the motor operation of large valves in steam power plants and in the chemical industry, the trend is toward extremely high pressures, up to 3000 lb. per sq. in., and relatively high temperatures. This has imposed unusual requirements as to the positive and accurate seating of the valves. Strains and resultant deformations may result from the pressures and from expansion and contraction of parts due to temperature changes. Also, dissimilar metals are used such as monel stems and chrome steel valve bodies, which have unlike temperature coefficients of expansion. Therefore the standard motor control with a mechanical limit set for an accurate number of turns of the yoke nut would, under certain conditions, not close the valve tight, or under other conditions it might seat the valve before this mechanical limit was reached and thus damage the valve seat.

To meet these conditions, a torque-limit valve control has been developed. This control assures the seating of the valve at a definite predetermined seating pressure, or a fixed torque of the motor.

The controller is provided with a mechanical limit which operates while the valve is still at an appreciable distance from the seat. When this limit operates a torque device relay is cut into circuit and as the valve approaches the seat, the seating pressure builds up, increasing the current passing through the motor until it reaches a predetermined value, at which time the motor is disconnected, properly seating the valve.

The control system allows full torque on the motor up to the actual tight seating point of the valve, and this type of control should be used for closing all Globe type of valves, and for gate type of valves on pressures exceeding 450 lb. per sq. in. and on temperatures of 500 deg. cent. and above.

*High-Speed Printing Presses.* The development of high-speed presses for printing newspapers and the tendency toward the use of a-c. power has produced new problems in the control and drive.

In operating newspaper presses a two-motor drive consisting of a small motor and a large motor, is generally used. The small motor operates through a gear train and overtraveling clutch, and is used to start, inch, and thread the paper through the press, at a speed of approximately 1200 papers per hr. The large motor which is connected direct to the press, drives it during the regular printing operation. The slowest speed required is for registering, which is at a speed of about 9000 papers per hr.

Newspaper presses operating at a maximum speed of 36,000 to 40,000 papers per hr., using 2, 3, and 4 press units of 16-page capacity each, are easily controlled and operated over the entire speed range either by d-c. adjustable speed motors or a-c. slip-ring motors, as the a-c. motors can be satisfactorily operated at a reduced speed equal to 25 per cent of normal, which is necessary to obtain the proper take-off speed. However, on high-speed presses operating at 60,000 papers per hr., the reduction in speed, without special provision, required on the a-c. slip-ring motor is so great that it results in breakage of the paper web during the transition period when the main driving motor takes the load from the starting motor.

To obtain satisfactory results on high-speed presses driven by a-c. slip-ring motors, a special control equipment has been developed. The objective is to obtain the same take-off speed for registering the web and to obtain the same pull on the paper web during the transition period, accelerating to the same printing speed as is obtained by means of regulating resistance in the secondary of the main motor on slower speed presses. To accomplish this a torque relay is used in connection with the equipment, which controls the torque of the press through a torque switch during the transition period. As the main motor accelerates, this torque relay controls the main motor and interrupts the acceleration when a certain speed and torque is reached. If, during the transition period, the speed falls below a certain point, this torque relay will again close the torque switch, tending to accelerate. The slight variation in speed obtained at this point is not perceptible and not objectionable from the printing standpoint.

The controller is operated from a push button station and when the web has been properly registered, the main motor can accelerate the press by manipulation of the push button station to the proper printing speed.

To date, a-c. control and drive equipments have been designed and operated on high-speed presses consisting of one and two 16-page units. Operating three or more presses together may involve some difficulties in collecting the paper webs.

*Paper Machine Drives.* A control system has been developed for giving remote control of the paper speed on sectional paper drives.

Sectional paper drives are generally operated by individual motors which are driven from a common generator and the speed is controlled by varying the voltage of the generator. In order to obtain stable speed the generator is provided with a voltage regulator.

In the past the voltage of the generator and the speed of the drive has been controlled manually at the motor-generator set, and the problem resolved itself into voltage control of the generator from a remote point and still keeping the generator under control of the voltage regulator at all times.

To obtain these results the voltage regulator operating by means of the torque produced in a moving electromagnetic system is used. Movement of this torque mechanism commutates the generator field current directly through regulating resistances. The torque system is connected directly across the voltage to be regulated and any voltage changes cause a displacement in the moving element because the torque produced in that element operates in opposition to an elastic recall system.

In order to compensate the regulator to cause it to regulate at a different voltage, it is only necessary to change the resistance in series with the torque coil. A motor operated rheostat which simultaneously commutates the generator field and the torque resistance is used to effect the voltage change. Proper space resistance relations of the two circuits maintains the voltage regulator in operation at all times.

The voltage regulator and the motor operated rheostat is controlled by a push button located at the machine floor and the speed changes are accomplished without the attendance of an operator at the switch control.

*Furnace Top Control.* A variable cycle furnace top controller for use in connection with the McKee revolving top has been developed.

In the past it has been the practise to revolve the furnace top with the load deposited from the skip pocket before dumping into the big bell in accordance with a fixed cycle. Most commonly six loads have been dumped in succession at six different dumping points. With the newly developed controller, it is possible to vary the number of loads dumped into the different positions from four to nine. This change in cycle is being obtained by a manually operated position switch on the panel. This type of control insures better distribution in the material in the furnace as it is possible to vary the cycle depending upon the grade of material.

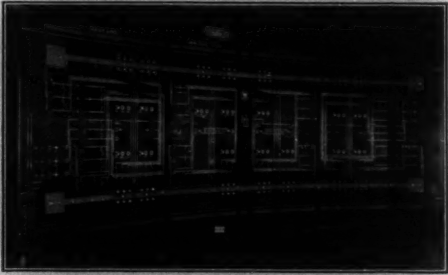

FIG. 20—SUPERVISORY CONTROL BOARD OF HOLLAND TUNNEL

*Holland Tunnel Supervisory Control.* The control equipment for the ventilation and operation of the Holland Tunnel connecting New York City with New Jersey has been designed to be handled by one man. This insures a maximum of safety with a minimum of operating force. The brains of this system is concentrated at the supervisory control board located on the top floor of the New York Administration Building. This board is built in the shape of an arc and composed of seven steel cabinets, as shown in Fig. 20, the cabinets being formed of sheets of ⅛-in. "stretcher-level" steel. At the rear and also within the cabinets are swinging steel doors, upon which are mounted the relays used on conjunction with the system.

The front of this board is a symbolic representation, both of a twin tube and the electrical circuit, including all feeders and motors. The board is divided by black vertical strips into five sections representing the four ventilation buildings and the mid-river sump. The names of the buildings are designated by name-plates shown near the top of the board. The two large trough-like castings running horizontally, one near the top and the other near the bottom of the control board, are symbolic of the north and south tubes respectively. The plateaus at the ends represent the plazas and the arrowheads indicate the directions of traffic.

Every oil circuit breaker control switch, motor speed switch, pump control switch, and their respective indicating lamps used in the tunnel equipment is duplicated on this board. By means of single direct-wire connections and the use of polarized type of relays, these various switches can control all the apparatus; likewise the lamps will indicate accordingly. The scheme of operation of this equipment is not at all like the standard supervisory control making use of the impulse method of using the automatic machine switching apparatus.

The control switches have a bar-like handle with the same finish as the miniature bus into which it is inserted. The position of this bar gives the operator a physical indication of the oil circuit breaker in addition to the indicating lamps. That is, when the control switch has been turned to close the breaker, the bar handle will be in line with the miniature bus. Likewise, when the switch has been turned to trip the oil circuit breaker, the handle of the switch will be left in a cross-wise position relative to the bus. When the control switch is turned to the closed position, its contacts impress a certain polarity over the single wire control to a receiving relay of the polarized type located in the ventilation building near the breaker. To trip same breaker the switch, when turned, will impress an opposite polarity on the receiving relay. The breaker lamp indication is brought back from the oil circuit breaker auxiliary switch to a receiving relay mounted on a swinging door in the rear of this control board; the same scheme of polarity that was used with the breaker control is employed also with the lamp indication.

At each breaker control switch, there is a green and white indicating lamp. The green lamp when illuminated, indicates that the breaker is closed. The white lamp has two degrees of brilliancy; the dim light indicates that the breaker has been tripped manually, while the bright light indicates that the breaker has been tripped automatically, due to some fault or failure.

The large lamp located on the raised part of the mimic tunnel, when illuminated, indicates what set of motors is feeding that particular section of the tunnel. The lamps on the upper raised section, above the trough indicates that the motors are being fed from the New York feeder, while the lamps on the lower raised station below the trough, indicates that the motors are being fed from the New Jersey feeder. Note that in order to insure continuity of service, each set of motors, consisting of a blower and exhaust, can be fed from either a New York bus or a New Jersey bus.

The large indicating lamp located in the trough of the mimic tunnel is connected to the carbon-monoxide recorder equipment. The illumination of this lamp indicates that there is more than two parts of carbon monoxide in 10,000 parts of air in the exhaust ducts. The small red lamp located in line with the carbon-monoxide lamp, when brightly illuminated, indicates that particular point in the tunnel from which the fire alarm has been sent in. The lights along the edge of the troughs close to the raised section, indicate what lighting cabinet is feeding the tunnel at that particular point.

On account of the method of ventilation used, the fans can be run on three different speeds. Consequently, the engineers selected motors of the wound rotor induction type so that speeds could be obtained by varying the resistance of the rotor. The three switches, grouped together in a vertical center line above the three large indicating lamps on the mimic tunnel, are for speed control. To select a particular speed, the key or handle must be inserted in the corresponding switch. In order to prevent the operator from forgetting to select a speed when he starts up any one of the fans in that particular section, an alarm will be sounded until the speed has been designated. The speed equipment consists of contactors with dashpots and a timing relay enclosed in a metal cabinet located near each motor in the ventilation building. The electric supply for the speed control is taken from a small distribution transformer located in the same housing as the breaker, which controls the main power circuit to the particular motor. As the motors can be fed from either New York or New Jersey bus, the small distribution transformers will be automatically fed from the respective bus.

As shown on the mimic tunnel, three fans feed each section of the ducts. One group of speed control switches is supplied for each section so that if three fans should be operating at the same time in the one section, all will be revolving at the same speed. A white indicating lamp is mounted directly above each speed switch; the lamp being illuminated above the corresponding switch of the particular speed selected.

On the lower half of the left-hand end of the control board are shown the three incoming feeders from power houses located in New Jersey, each feeder being 13,200 volt, three-phase, 60 cycles. On the upper half of the right-hand end of the board are shown in a similar manner the three incoming feeders, having the same characteristics as those from New Jersey, from power houses located in New York. In line with the miniature bus for these feeders, are white indicating lamps which are known as bus potential pilot lamps. These lights have also two degrees of brilliancy, when dim indicate that the feeder is alive; when bright indicate that due to some abnormal condition, the feeder has been opened. The lamp extinguished indicates that the bus is dead.

The incoming lines feed three-winding, air-blast, power transformers, which have secondary voltages of 2300 and 440 volts, these potentials being required for the motors. All oil circuit breakers are of the truck type design. The 13,200-volt incoming lines, all tie breakers, and the 2300-volt motor breakers are of the standard design, while the 440-volt motor breakers, on account of their number, are built in two tiers in order to save space.

All the protective relays used on the incoming feeders and motor circuits are located in the various ventilation buildings near the respective motors. The incoming lines are protected against short circuit. The three-winding power transformers have differential protection. The motors are protected by thermal overload relays which take care of excessive temperature rise due to overload. This same relay has a short circuit element which will act instantaneously if a short circuit occurs. To protect the motor during the starting and stopping period against failure of the speed control devices, and for protection, should the dampers within the air ducts be closed while the motors are running, a long time-delay undervoltage relay has been supplied.

From the above description of the supervisory control system and its control board, the supervisory operator knows and sees exactly how every piece of apparatus composing this gigantic network is performing. He can tell whether the incoming line breaker is still feeding the equipment, or whether it has tripped out automatically; whether or not the designated fans are running properly at the selected speed; whether the percentage of poisonous gas is dangerous in any section of the tunnel; if a fire alarm has been sent in, and what section is affected. The level of the water in the various sump chambers can be determined by certain lamp indications. Should any change be made in the position of any particular apparatus, due to some fault or failure, a bell alarm will be sounded and a bright light will indicate the location and character of the trouble.

## Miscellaneous Applications

*Brick and Clay Industry.* This industry is rather behind in the application of electrical power, the usual excuses being those of excessive dust, sulphur fumes, etc. These excuses are proved fallacious by installations in other industries. In one of the large Hudson River soft mud plants a complete electrified installation is now being built.

The superiority of electrical power over steam in clay plants is becoming universally acknowledged and practically all new plants are so equipped.

*Ceramic Industry.* Electrical energy is now recognized as an ideal fuel, particularly for ceramic manufacturers. It produces very clean heat, simplifies furnace construction and produces the highest percentage of No. 1 ware.

*Textile Industry.* Electric heating was adopted for the first time to the cloth singeing machines which are used in the finishing rooms of textile mills. The singeing was previously done by gas or oil heat.

Most of the singeing machines in operation at present are of the horizontal type with burners or hot contact plates mounted in horizontal rows so that the cloth is in a horizontal position in its travel over them. By the adoption of electric heating units, it was possible to arrange them vertically over each other in two rows, so that the cloth would be in a vertical position when traveling over them.

This arrangement not only makes available the close control of the temperature which is characteristic of electric heating, but it also reduces the floor space required for the machine.

*Bottle Making.* The *Electrician* of November 4, 1927 describes a new machine put out by European manufacturers which makes over 5000 large bottles an hour and smaller ones at a higher rate. The machine is driven by a 15-hp. adjustable speed motor and is equipped throughout with roller or ball bearings.

*Lighting.* The application of an electric flashing system and a lantern of new design displaced kerosene buoy lights on the New York Barge Canal.

Artificial light has been further used in the horticultural field.

There has been a large increase in the application of lighting of special kind in the medical field where cures can be effected by the equivalent of sun rays.

Also in the medical field should be mentioned the application of cathode rays and their effects in the production of vitamines in yeast and other foods. This research has been aided by the development in 1927 of cathode ray tubes for operating potentials of 900,000 volts. In 1926 the maximum operating potential was 400,000 volts. The higher potential has increased the velocity and range of the cathode ray discharge.

Under lighting should be mentioned the enormous increase in applications of neon tubes for commercial advertising. Also the development of a new type quartz neon gas-filled lamp which resembles a ball of reddish orange fire and has great fog penetrating possibilities.

A unique application of lighting is towards the elimination of certain moths and insects.

Flood lighting has been applied to harvesting operations and to the lighting of athletic fields for night sports.

*Synchronous Motors on Centrifugal Pumps.* The use of synchronous motors on centrifugal pumps is increasing as is noted by the demand for 1800-rev. per min. and even 3600-rev. per min. synchronous motors for this purpose.

*Oil Engine-Driven Alternators.* A 3750 kv-a., 124-rev. per min., 60-cycle alternator for direct connection to a Busch-Sulzer oil engine is being erected by Tucson Gas, Electric Light & Power Co.

*High-Voltage Transformers.* Three 500-kv-a., 750,000-volt transformers have been installed by the Ohio Insulator Co. of Barberton, Ohio. In this installation, the three transformers are connected in series and are thus capable of developing 2,250,000 volts above ground. This is said to be considerably higher than that developed by any other transformers in the world.

*Individual Wire Blocks.* The application of individual d-c. drive for wire blocks has rapidly increased. Between 350 and 400 blocks have now been installed in such a drive. The principal advantages are the flexibility of the individual drive since the wire block may be operated at any speed desired for the particular work at hand; smooth easy start which can be secured with direct current and the consequent control advantages in starting the wire through the die; the safety features which may be introduced in d-c. motors and control.

*Ward Leonard Control.* It is very interesting to note the number of new applications that have been found for this old principle. By the use of Ward Leonard control combined with field weakening on the motor, speed ranges as great as 20 and even 30 to 1 can be secured. With such a Ward Leonard system the control is very inexpensive and goes quite a long way toward paying for the extra expense of an individual generator. This type of drive has been used on galvanizing take-up frames in several instances.

*Tandem Drive for Strip Mill.* Several continuous strip mills have been installed in the last year with individual motor drive in each of the mills where the material is in several mills at the same time but without any loops in the steel. This can be accomplished by d-c. motors if the motors are carefully tested and calibrated to operate together with special provision in the fields for keeping the motors in correct speed relations, without developing a loop or stretching the steel.

*Anti-Friction Bearings.* The use of ball and roller bearings in motor applications has increased at a rapid rate. Many companies use this type of bearing exclusively. One company reports good success with the use of tapered roller bearings and the extension of their use to vertical motors, both alternating current and direct current, with very satisfactory results. The thrust capacity of the tapered roller bearing makes it ideal for many applications.

*Totally Enclosed Fan-Cooled Motors.* The totally enclosed, fan-cooled motor fills a demand for a moderately priced machine to successfully operate in the presence of dust or gas that has a deteriorating effect on insulation. These are generally of two types, those with external fans at both ends of the motor, which take in the outside cooling air at both ends and blow it towards the center, and those with fans at one end only, the cooling air being either drawn or blown across the motor from end to end. There is a constantly increasing demand for these fan-cooled enclosed motors and conditions indicate a considerably greater production this coming year.

*Texrope Drive.* This is a comparatively new development and was mentioned in a previous report of this committee. It is interesting to note that repeated tests show a transmission efficiency of 99 per cent for recommended maximum load. The large coefficient of friction allows the transmission of full power with a small tension on the loose side of the drive and successful operation with minimum bearing pressures.

# Mining Work

## ANNUAL REPORT OF THE COMMITTEE ON APPLICATION TO MINING WORK[*]

*To the Board of Directors:*

In reviewing recent progress made in the application of electrical power in mines, one is inclined to conclude that it has been effected by the general economic conditions prevailing in the mining industry. Over-production facilities in men and mines, labor problems, and freight rates are factors which are vitally influencing the prosperity and accomplishments of the business.

Conferences of mine managers and manufacturers of mining equipment, together with the meetings of engineering societies, indicate that the mechanization of mines is making great progress; in fact, definite conclusions have been reached that, under many conditions, mechanization pays. Considering the great investment required, and the new problems arising in the concentration of men, equipment, and supplies, creditable economies are being effected in the mechanical loading of coal where but an average tonnage is obtained from the equipment. Mine managers are realizing that the successful loading of coal is not solved by the purchase and installation of the machine, but that it involves many other operations, such as mining the coal, car dispatching, transportation, and mine planning. The question of cleaning the coal must also be included, since machine-loaded coal contains the impurities which, in hand loading, are left in the mine.

In 1926, about ten million tons of bituminous coal were loaded mechanically by 455 machines, this being an increase of approximately 60 per cent over 1925. While no complete reports are available at the present time concerning the number of machines in operation during 1927, certain information indicates that there will be a decided increase over those used in 1926. Due to the suspension of mining in Illinois and Indiana, the tonnage loaded in 1927 will not show much increase.

As the mechanization of mines continues, so does also the demand for equipment approved by the United States Bureau of Mines. This is due to the fact that much of the equipment required in mechanical loading and conveying machinery is used at the face workings where the maximum danger from gas and dust exists. The use of electrical equipment approved by the Bureau of Mines is becoming so general that there is in operation a bituminous coal mine with a daily output of 3500 tons, in which all of the underground electrical apparatus carries the permissible plate of the Bureau. Power for the motors in the mine is supplied by storage battery power trucks.

In some mines, mechanical loading means the use of several 125-hp. scraper hoist motors. A loading system of this type requires the transmission of power at 2200 volts. Proper protection is attained when using electricity at the above voltage, by the use of metallic armored cables placed in intake airways, and supported by a steel messenger wire. A cable crossing a track is taken underneath it in a conduit or concrete duct. Branch line taps are safeguarded with the usual protected oil switches.

The maintaining of a satisfactory d-c. voltage at the working face becomes more important each year. A 200-kw. portable rotary converter with its necessary accessories has been profitably used to attain such results. The transformers, switchboard, and control panels are mounted on trucks with the same gage as the mine tracks. A special frame structure is bolted to the converter making it possible to attach a truck to it. A movement of the entire station is contemplated every six months. Experience has shown that a complete move requires a period of eight hours.

An improved electric cap lamp consisting of a two-filament gas filled bulb and a bakelite head piece has been placed on the market. The new bulb produces more light, and the head piece, being an insulator, reduces the possibility of accident when worn in the vicinity of electrical conductors. When the main filament burns out, the auxiliary filament may be turned on, thereby enabling the miner to complete his day's work or come out of the mine. As the intensity of illumination in the mines is increased, greater safety may be expected, and no doubt an improvement in the efficiency of labor will follow.

Comprehensive dispatching systems are being placed in operation, their success depending upon a more general use of telephonic and automatic signal systems. In large mines, a system of this type is necessary to get the highest operating efficiency from the haulage system. Telephones are used to distribute the cars, and a signal system moves the trains over the main haulage roads. These systems relieve the mine foremen of considerable detail work, and give them more time for other important mine management problems.

The haulage costs in mines with a large output are being reduced by the introduction of larger mine cars and heavier locomotives. Main line locomotives equipped with three axles and weighing 35 tons are now being used in mines where two-axle locomotives were too small for economical operation. Locomotives of this type have an electropneumatic control, air brakes, and dynamic braking for handling loads on down grades.

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[*] **APPLICATIONS TO MINING WORK:**

**W. H. Lesser, Chairman.**

**F. N. Bosson,**
**Graham Bright,**
**M. M. Fowler,**
**E. J. Gealy,**
**L. C. Ilsley,**
**G. M. Kennedy,**
**R. L. Kingsland,**
**A. B. Kiser,**
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**E. D. Stewart,**
**F. L. Stone,**
**W. A. Thomas,**
**E. B. Wagner,**
**J. F. Wiggert,**
**C. D. Woodward.**

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

An increase in the motor capacity of large locomotives is being obtained by the use of forced ventilation, which is produced by a separate motor-driven blower mounted on the locomotive. The ventilation of the motors has been found to double their continuous rating. Notwithstanding the additional equipment necessary for ventilating the motors, the results obtained are so satisfactory that it has been adopted as standard practise by some manufacturers building three motor locomotives weighing 25 to 35 tons.

The largest mine locomotive ever built has been recently placed in service. It weighs 38 tons, has a 36-in. gage, and semi-elliptic leaf type springs with a three point equalization. Three 133-hp., 500-volt d-c. motors with forced ventilation will furnish the power. A semi-magnetic control arranged for series parallel operation of the motors in either direction constitutes the control equipment. The drawbar pull on level track at 33⅓ per cent adhesion will be 23,333 lb. at a speed of 7.4 mi. per hour.

Mechanical loading has concentrated and increased the service required from gathering locomotives to such an extent that heavier and slower speed locomotives are proving to be the best type. A reduction in the speed of gathering locomotives to 3½ mi. per hour makes it possible to do the same work with a consumption of 30 to 40 per cent less power.

The transportation of coal long distances by belt conveyors instead of locomotives is making progress. Mines in which the coal travels from the face to the tipple on conveyors are possibilities.

The world's largest electrically operated shovel will go into operation during this year in the open-pit mines of Illinois. It is equipped with a 15-cu. yd. dipper, and a boom 120 ft. long. Two 450-hp. motors will provide the power for hoisting, and two 150-hp. motors will do the swinging. A Ward Leonard control will be used, involving a motor generator set, the synchronous motor of which will have a capacity of 1700-kv-a. Shovels of this size will reduce the unit cost of the material handled, and make it possible to increase the ratio of overburden to coal in strip mining.

Where gaseous mines are being supplied with electrical power from large public utility plants over long transmission lines, installations are being made which will make it possible to operate the fans, and to hoist the men during periods when the normal supply of power has failed. An installation of this type consists of two fans, and a man hoist driven by a-c. motors, three-phase, 60 cycles, and 2200 volts. When an interruption of the power occurs, the above equipment is supplied with power at 40 cycles, and 1500 volts. Under these conditions, the control apparatus will function properly, and the motors will operate at two-thirds speed, which is sufficient to keep the mine clear from gas and to hoist the men. The emergency power is produced by a gasoline-engine-driven, 200-kv-a. generator capable of being started by a push-button in case of a power interruption.

A notable electrification program of a large copper mining company has just been completed. The complete electrification of its 28 mines with a connected motor load of about 65,000 hp. shows that electrical power is an important factor in the copper industry. Engineers have overcome many difficulties in the installation and maintenance of electrical apparatus in copper mines, where the action of copper sulphate is so harmful.

In another open-pit copper property, there are 23 electrically-operated shovels in service. This year the entire steam haulage system consisting of 52 steam locomotives will be replaced by 37 trolley locomotives each weighing 75 tons.

In hard rock ore mines, as distinguished from coal mines and other soft ore mines, experiments are being conducted on the electrical equipment required by loaders, slushers, and other machinery. Much progress is being made in the adaptation of motors to this exceptionally severe service.

Automatic controls for mine substations, fans, pumping plants, and air compressors are being continually developed and placed in operation. At the present time there are about 200 automatic pumping stations in operation in the anthracite coal field, representing an annual saving in labor cost of approximately $500,000. The automatic stopping and starting of air compressors has been developed and several are in successful operation.

A rather unique application of electricity in the mining industry consists in using it for heating the bathing water for those employees who work on holidays or during periods when most of the regular force is idle. In one instance, a steam plant is necessary to heat the water for the normal force of 600 men, while during idle days, immersion heating units in a tank provide sufficient hot water for the reduced force of 25 men.

It is becoming more noticeable each year that the managers of the mines are giving more attention to the maintenance and care of the electrical equipment, resulting in a decreased maintenance cost and a better operating efficiency. The mine electrician in charge of the electrical equipment is given more authority and is directed by the electrical engineer in all technical questions. Frequent inspections of the mine by the engineer and the electrician, together with a good operating organization materially reduce the number of equipment failures, so disastrous to good production.

# Marine Work

## ANNUAL REPORT OF COMMITTEE ON APPLICATIONS TO MARINE WORK*

*To the Board of Directors*:

The activities of the Committee on Applications to Marine Work this year were devoted chiefly to the dissemination of the Marine Standards (A. I. E. E. Standard No. 45), cooperation with the N. F. P. A. (Committee on Fire Detection and Alarm), cooperation with the American Marine Standards Committee on specifications for water tight receptacles, and the expenditure of further efforts to induce the U. S. Steamboat Inspection Service to recognize and properly classify the electrical engineer on shipboard.

A. I. E. E. Standards No. 45 were issued in June 1927. The committee this year made a special effort to distribute the Standards to all departments of the marine industry likely to be interested and as a result of this campaign 750 copies were sold.

The Standards are recognized and accepted by the various marine classification and insurance societies, naval architects and marine engineers, and are incorporated as one of the regulating provisions in their specifications. A. I. E. E. Standards No. 45 are therefore a recognized success and will serve to standardize the electrical installations on shipboard and to stimulate the use and proper care of electrical machinery in the marine field.

The Conference Committee on Fire Detection and Alarm requested our cooperation in connection with recommendations which it was preparing for the Steamboat Inspection Service, of fire alarm and fire detecting systems. In compliance with this request, our committee reviewed its proposed recommendations in detail and subsequently held a joint meeting with its representatives, at which all points of difference were discussed.

The committee also cooperated with the special committee on water tight receptacles appointed by the American Marine Standards Committee of the Bureau of Simplified Practise, to draw up specifications for water tight receptacles for shipboard service.

Considerable time was spent in connection with the proposition of inducing the U. S. Steamboat Inspection Service to make provision in its regulations for the proper rating and classification of the electrical engineer on shipboard. To this end, our committee prepared its report containing a statement of the status of the present electrical personnel, reasons for higher and proper rating and recognition of the electrical engineer on board ship, together with a suggested list of ratings and grades for the electrical personnel of the various classes of ships. These recommendations were made in such manner as to permit licenses in the different electrical grades being taken out by those of the present steam and Diesel classified engineers who qualified.

This report was presented by our subcommittee on personnel at the annual meeting of the U. S. Steamboat Inspection Service in Washington in January. Although final action was deferred by the Steamboat Inspection Service at its annual meeting, it decided to take our recommendation under consideration in the regular routine of its body and prepared plans to circularize the marine operators for the purpose of soliciting their opinions in the matter of classifying electrical personnel. It is felt that favorable action will be taken by the Steamboat Inspection Service and its regulations modified in the course of time. Our subcommittee on personnel is keeping in close touch with the situation.

In addition to the above chief items considered by the committee this year, the question of revision of present specifications was taken under advisement and arrangements made to keep the specifications up to date automatically by considering and acting upon all proposed changes as they are presented. In this way the time and effort required to get out the revised issue when necessary will be considerably minimized.

The outstanding electrical developments in the marine field during the past year are as follows:

1. The construction of five 3000-ship hp. turbine-electric drive U. S. Coast Guard Cutters.
2. The placing in service of the S. S. *California*, an 18,000-ship hp. twin-screw turbine-electric drive passenger ship for the Panama Pacific Steamship Line. A sister ship to the *California* is now under construction.
3. The conversion by the U. S. Shipping Board of three of their largest cargo vessels (*Courageous*, *Defiance*, and *Triumph*) to Diesel electric drive. These vessels will have machinery suitable for 4000-ship hp. normal and 4500-ship hp. maximum continuous.

Besides the above chief developments there has been a number of smaller craft equipped with electric propulsion. The application of electrical equipment to ships is continuing at an increasing rate and the future looks hopeful indeed.

With the passage of the Jones-White bill and its approval by the President, the American Merchant Marine has received its first real encouragement since the World War period. This bill contains several provisions which will undoubtedly stimulate the American marine industry. We can anticipate rapid developments in which electricity will play a very important rôle.

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*APPLICATIONS TO MARINE WORK:

W. E. Thau, Chairman,
R. A. Beekman, Vice-Chairman,
J. L. Wilson, Secretary,

Edgar C. Alger,
H. C. Coleman,
E. M. Glasgow,
H. Franklin Harvey, Jr.,
Wm. Hetherington, Jr.,
H. L. Hibbard,
J. S. Jones,
A. Kennedy, Jr.,
J. B. Lunsford,
E. B. Merriam,
I. H. Osborne,
G. A. Pierce,
Wm. H. Reed,
Edgar P. Slack,
H. M. Southgate,
C. P. Turner,
Oscar A. Wilde,
R. L. Witham.

*Presented at the Annual Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

# Electric Transportation

## ANNUAL REPORT OF COMMITTEE ON TRANSPORTATION[*]

*To the Board of Directors:*

The application of electricity to transportation proceeded during 1927 at a healthy rate, and new developments in apparatus and equipment continued, several interesting applications being introduced during the year.

### Steam Railroad Electrification

Although no new electrification projects of major importance were completed during the year of 1927, two extensions were opened which had as their particular aim the further simplification of electric operation already existing, *viz.*, the Bay Ridge extension of the Long Island Railroad permits electrically-operated freight trains from the New York, New Haven & Hartford Railroad to pass over the Hell Gate Bridge Route to the tidewater freight terminal at Bay Ridge, Long Island; the Chicago, Milwaukee, St. Paul & Pacific Railroad has electrified its passenger terminal in Seattle, Washington, together with its line from Black River Junction over which trains had previously been handled by steam power.

Of the incompleted projects: the Pennsylvania Railroad will place in service shortly its suburban electrification from Broad Street Station, Philadelphia, to Wilmington, Del. and West Chester, Pa. The Great Northern Railway is proceeding with the extension of electric operation from Cascade Tunnel to Wenatchee, Washington. The New York Central Railroad is electrifying its west side freight yards in New York City. The New York, Westchester & Boston Railway is continuing its line to Port Chester, N. Y. The Detroit, Toledo & Ironton Railroad is working on the extension of its existing electrification from Flat Rock on to Petersburg, Mich.

The principal new project getting under way at the present time is the electrification of the suburban lines of the Reading Company around Philadelphia, Pa. It has been announced also that the Boston, Revere Beach & Lynn Railroad is planning to electrify its line.

Of electrifications placed in service during the year of 1926, one of the most interesting, the Chicago Terminal electrification of the Illinois Central Railroad, reports a marked increase in traffic and revenue for the first year of operation.[1]

*Long Island Railroad.* The Bay Ridge extension of the Long Island Railroad has been electrified with the 11,000 volt overhead catenary, single-phase, 25-cycle system for freight operation. This line joins the Bay Ridge freight terminal of the Long Island Railroad with the New York Connecting Railroad's Hell Gate Bridge Route to the New York, New Haven and Hartford Railroad at Port Morris, N. Y. The route is 20 miles in length.

Power is transmitted over a 22,000-volt, three-wire system with 11,000 volts between trolley and ground, and is received from the New Haven Railroad distribution system; in emergency it can be obtained from one 5000-kw. variable ratio frequency changer at the Long Island's East New York substation. This frequency changer is normally used as a synchronous condenser for power factor correction. No. 4/0 copper feeder wires are connected to the trolleys through auto-transformers at six balancer substations, four of which are on the Long Island and two on the New York Connecting Railroad.

The catenary system is non-ferrous with a single 4/0 bronze contact wire, copper auxiliary wire and high-strength bronze messenger wire. Inclined catenary is used in general on curves. The supports consist largely of rolled structural "H" beams. Rails are bonded with two No. 1 copper, 37-strand flame-welded bonds per joint.

The seven double-unit, gear-drive locomotives built for switching service have a wheel arrangement of 0–6–0 + 0–6–0, and weigh 158 tons each. The six motors on each complete locomotive are rated at 235 volts and operate with forced ventilation. The maximum starting tractive effort is 100,000 lb. and can be obtained up to 7½ mi. per hour. The maximum operating speed is 25 mi. per hour. Through traffic is handled by New Haven locomotives.

In addition to the Bay Ridge a-c. electrification, the Long Island Railroad is adding to its d-c. operation to the extent of 75 mi. of freight tracks and sidings, which will allow electric operation of all freight service within the electrified portion of the railroad. The work is 50 per cent completed and is to be completed by October 1st, 1928. A special "T" section third-rail of high conductivity is being used for all sidings and yard tracks.

*Chicago, Milwaukee, St. Paul & Pacific Railroad.* The western terminal of the Chicago, Milwaukee, St. Paul & Pacific are Seattle and Tacoma, Washington. Electric service ran into Tacoma, and service to Seattle had been handled by steam from Black River Junction. During the year of 1927, the line, 10 mi. of double track from the junction into Seattle, was electrified. Power is furnished from the earlier electrification through the overhead distribution system, and no new substations were constructed. This electrification is 3000-volt,

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[*] COMMITTEE ON TRANSPORTATION:

J. V. B. Duer, Chairman.

Reinier Beeuwkes,
E. R. Hill,
W. K. Howe,
D. C. Jackson,
John Murphy,
W. S. Murray,
W. B. Potter,
N. W. Storer,
H. M. Vandersluis,
Richard H. Wheeler,
Sidney Withington.

[1] *First Year of Electric Operation in Chicago*, by W. M. Vandersluis, A. I. E. E. Quarterly Trans., Vol. 47, 1928, No. 1, p. 217.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

d-c., with an overhead catenary system having a double contact wire.

*Pennsylvania Railroad.* The Pennsylvania Railroad is completing the electrification of its suburban service from Philadelphia, Pa., to Wilmington, Del., on its main line to Washington, and to West Chester, Pa., on the Wawa Branch. This project was outlined in last year's report. Overhead catenary is used, energized with 11,000-volt, 25-cycle, single-phase current.

*Great Northern Railway.* The project of the Great Northern Railway to electrify its line between Wenatchee and Skykomish, Wash., is proceeding rapidly. Grade and curvature realinements are being made, and the new Cascade Tunnel from Berne to Scenic, (7.79 mi. long) is more than 65 per cent completed. Electric operation, which now extends from Skykomish through the old Cascade Tunnel, is to be extended through the new tunnel and on to Wenatchee before the end of 1928. The project will operate on 11,000-volt, single-phase, 25-cycle power, using motor generator locomotives with d-c. traction motors.

Orders have been placed for locomotives similar to those which are now in operation; that is, two additional type 2-6 + 6-2 and two additional type 2-8-2 + 2-8-2 locomotives, having continuous ratings of 3000 hp. and 3660 hp. respectively.

*New York Central Railroad.* The New York Central Railroad is proceeding with the electrification of its west side yards in New York City. The overhead trolley system at 600 volts d-c. is to be used as far down town as 60th Street. Below this the motive power will be self-contained power units.

*New York, Westchester & Boston Railway.* The New York, Westchester & Boston Railway is completing the extension of its Port Chester, N. Y., line as far as Rye, N. Y. Multiple unit suburban service is operated on 11,000-volt, 25-cycle, single-phase power.

*Detroit, Toledo & Ironton Railway.* The Detroit, Toledo & Ironton Railway is proceeding with the electrification of 26 mi. of line from Flat Rock to Petersburg, Mich. This will be an extension of the existing 11,000-volt, 25-cycle, single-phase electrified line described in last year's report, which runs from Fordson to Flat Rock, Mich.

*Reading Company.* The Reading Company is planning extensive improvements in its Philadelphia facilities, and expects to electrify 85 mi. of track with a 11,000-volt, 25-cycle, single-phase system.

Power will be furnished to this electrification over 22,000-volt feeders by a three-wire system with 11,000 volts between the overhead catenary and ground. The eventual program calls for transmission between substations at 66,000 volts.

The initial project comprises multiple unit service from the Reading Terminal in Philadelphia to Chestnut Hill, to Lansdale on the Bethlehem Branch and to Hatboro.

*Boston, Revere Beach & Lynn Railroad.* The Boston, Revere Beach & Lynn Railroad, a narrow gage line running out of Boston, Mass., plans to electrify a route of 15 mi. It is proposed to use a 600-volt overhead catenary system for multiple unit operation.

### CITY AND SUBURBAN RAILWAYS

On electric street railways increased acceleration is being obtained by the use of light weight cars and more powerful motors with the latest design of control, thus tending to relieve congestion on city streets.

Trial installations of the new type of drive mentioned in last year's report have been put in service in a number of instances. This is the automotive type propeller-shaft drive by which unsprung weight is greatly reduced, with a corresponding reduction in noise and maintenance. Improved installations have been made in reduction gear drive with entirely spring-suspended motors having a flexible driving joint.

### MARINE PROPULSION

The largest turbine-electric passenger ship, *California*, was launched October 1st, 1927. The displacement is 30,250 tons. Power is supplied to the propellers by two synchronous induction type motors each with a maximum continuous rating of 8500 ship hp. at 120 rev. per min.

The installation of Diesel-electric drive has been extended during the year to include three new lightships for the Department of Commerce as well as coast guard cutters, large double-ended ferry boats, a packet boat, and cargo boats.

### BUS TRANSPORTATION

Gas-electric drive for motor buses and motor coaches is increasingly popular. Experiments have been made on electric transmission for taxicabs.

### RECENT DEVELOPMENTS

*Diesel Electric Locomotives.* The past year brought forth a novel arrangement of the Diesel engine prime mover with electric drive:

In electrification of its west side yards in New York City the New York Central Railroad has decided to use an overhead contact wire within the city limits only as far down town as 60th Street. Below this point it is desirable to employ a self-propelled unit. The locomotive chosen for this service, therefore, operates on third rail or trolley at 600 volts d-c., or can be propelled by power from a self-contained 300-hp. Diesel engine-driven generator, augmented for peak requirements by a storage battery. When load requirement is for less than 300 hp. the current from this battery is replaced by the generator.

*Gasoline-Electric Rail Cars.* During the year of 1927, approximately 150 gasoline-electric motor rail cars were ordered by the railroads of the United States. One 300 hp. oil-electric car was placed in service.

*Trolley-Storage Battery Locomotive.* Two electric locomotives furnished with power from a storage battery and also from an overhead trolley wire are in service for yard switching service on the Chicago, North Shore & Milwaukee Railroad. When the locomotive is receiving current from the trolley the battery is charged by a motor-generator set.

*High-Speed A-c. Circuit Breakers.* Although oil circuit breakers with rapid operating characteristics have been available for several years in a-c. switching, one of the most interesting developments of the past year has been the construction of an air circuit breaker for operating on 11,000-volt a-c. circuits and having speed characteristics similar to d-c. installations This type, as well as oil circuit breakers operating on the same principle, is to be used by the Pennsylvania Railroad on its extension of electrified suburban service around Philadelphia.

*Overhead Catenary.* The construction of overhead catenary on the Great Northern Railway electrification from Skykomish to Wenatchee, Wash., is an application of the formula proposed by O. M. Jorstad[2] for inclined catenary.

*Supervisory Control.* All four transformer substations on the Philadelphia to West Chester electrification of the Pennsylvania Railroad are to be controlled from the Wawa signal tower by supervisory control. The synchronous visual type is being installed.

Another interesting installation of supervisory control is the West Hempstead substation of the Long Island Railroad, now under construction, at which three 1000-kw. mercury arc rectifiers are controlled from Mineola substation two miles away. The rectifiers can be started by the supervisory system in approximately 20 sec.

*Train Communication.* Radio communication between locomotive and caboose and between train and station has been the subject of considerable experiment. An installation of this type is in service on the New York Central Railroad.

*Mercury Arc Rectifiers.* The use of the mercury arc rectifiers in electric railway substations is still limited to a few installations. A summary of the operating experience of one railroad with this equipment is contained in a paper entitled *Operation and Performance of Mercury Arc Rectifiers on the Chicago, North Shore & Milwaukee Railroad Company.* This paper was presented by Caesar Antoniono at the Regional Meeting[3] in Chicago, Ill., November 28-30, 1927.

## TECHNICAL PAPERS

The committee has obtained for presentation at the 1928 Summer Convention a group of interesting papers. They are as follows:

*High-Speed Circuit Breakers,* by J. W. McNairy, General Electric Company.

*The High-Speed Circuit Breaker in Service on the Illinois Central Railroad,* by W. P. Monroe and R. M. Allen, Illinois Central Railroad.

*Arrangement of Feeders and Equipment for Electrified Railways,* by R. B. Morton, Gibbs & Hill, New York, N. Y.

*Operating Experience with High-Speed Oil Circuit Breakers,* by B. F. Bardo, New York, New Haven & Hartford Railroad.

*High-Speed Circuit Breakers for Railway Electrification Work,* by H. M. Wilcox, Westinghouse Elec. & Mfg. Co.

*Protection of Electric Locomotives and Cars to Operate with High-Speed Circuit Breakers,* by E. H. Brown, Pennsylvania Railroad Co.

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[2] *Standardized Catenary Design,* by O. M. Jorstad, A. I. E. E. TRANS., Vol. 46, 1927, p. 1125.

[3] A. I. E. E. QUARTERLY TRANS., Vol. 47, 1928, No. 1, p. 228.

# Electric Welding

## ANNUAL REPORT OF THE COMMITTEE ON ELECTRIC WELDING*

*To the Board of Directors:*

During the past year, marked progress has been made in the application of electric welding to an increasing number of industrial uses including welding of pipe, pipe lines, structures, and cracking stills for gasoline production. A few outstanding applications are mentioned by way of example in the following paragraphs.

One of the largest welding jobs completed during the year was the Mokelumne River Project, a pipe line supplying water to Oakland and other Bay Cities near San Francisco. This line is 90 mi. long. The pipe is 66 in. in diameter and its thickness varies from 3/8 in. to 5/8 in. depending on the water pressure in the particular section of pipe. This job is completed and is, so far as known, the largest single job of welding which has ever been undertaken.

This pipe was so large that it was necessary to join two plates in order to get the required diameter, one joint being made on each side of the pipe. These were welded by the automatic carbon-arc welding process. After each section of the pipe was welded, it was tested by hydraulic pressure at a fiber stress of about 23,000 lb. per sq. in., and while under this pressure, heavy sledges were dropped from a 4-ft. height on each side of the joint, the sledges being one foot apart. This gave a shock test to the joint at the time when it was subjected to the maximum hydraulic pressure.

The contract price on this job of arc welding was twelve million dollars. The best figure offered for the same pipe riveted was fifteen million dollars.

During the year, 45 mi. of 7-in. oil pipe line was electrically arc welded in Louisiana. The pipe was made in the ordinary way and the ends of the pipe were welded. The chief advantage of this method is that the finished pipe line is free from the leakage that sometimes occurs at joints made by threaded couplings in the old way.

This pipe was welded at $1.25 per joint contract price. According to the people who did the welding, the actual cost was 58 cents per joint. The best proposition for welding this pipe by any other method than the metallic arc was $2.75 per joint.

During the year, a number of cracking stills for the production of gasoline from crude oil were welded by the A. O. Smith Corporation. They have been put into service for carrying pressure as high as 1000 lb. to the square inch and a temperature as high as 900 deg. fahr. This is work which can be done only by the welding process. The results cannot be accomplished at all by the older riveting process.

Four papers on electric arc welding were presented at the Winter Convention of the Institute. One of these papers by J. B. Green[1] of the Fusion Welding Corporation dealt with the influence of the covering of the electrode on the characteristics of the arc. During its presentation slow-motion pictures of the arc taken with infra-red light were shown. These disclosed how the metal goes across the arc from the electrode to the work.

The paper by P. Alexander[2] of the Research Department of the General Electric Company at Lynn, Mass., dealt with the influence of the surrounding atmosphere on the arc.

The paper by A. M. Candy[3] of the Westinghouse Electric & Manufacturing Company described a five-story building recently erected by welding, and a paper by A. P. Wood[4] of the General Electric Company described what is being done at Schenectady in the way of welding electric machines of all descriptions.

Since that time, a bridge has been erected by welding by the Westinghouse Company at their plant at Chicopee Falls. This bridge has 80 tons of structural steel in its construction and would have required 120 tons if it had been erected by the riveting method in the regular way.

Early in 1928 three prizes offered by the Lincoln Electric Company for the best papers on electric arc welding through the American Society of Mechanical Engineers were awarded by a committee of seven judges representing the Engineering Societies and the Bureau of Standards.

The first prize of $10,000 was awarded to J. W. Owens of the Newport News Shipbuilding & Dry Dock Company, for a paper on "Electric Arc Welding in Ship Construction."

The second prize of $5000 was awarded to Professor H. Dustin of Brussels, Belgium, for a paper covering the method of calculating the strength of welding, giving data not heretofore available.

The third prize of $2500 was awarded to H. E. Rossell of the Philadelphia Navy Yard on the use of electric arc welding in the construction of bulkheads.

The American Welding Society has had committees on structural-steel welding and on pressure-vessel welding at work during the year and substantial progress has been made in the work of the committees, although no final report has been issued.

J. C. LINCOLN, *Chairman.*

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*COMMITTEE ON ELECTRIC WELDING:

J. C. Lincoln, Chairman.

C. A. Adams,
P. P. Alexander,
C. W. Bates,
Ernest Bauer,
A. M. Candy,
Alex. Churchward,
O. H. Eschholz,
F. M. Farmer,
H. M. Hobart,
C. J. Holslag,
C. L. Ipsen,
Ernest Lunn,
J. W. Owens,
William Spraragen,
H. W. Tobey,
Ernest Wanamaker.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

[1] A. I. E. E. Quarterly TRANS., No. 2, Vol. 47, 1928, p. 820.

[2] Ibid., p. 706.

[3] Ibid., p. 711.

[4] Ibid., p. 717.

# Iron and Steel

## ANNUAL REPORT OF COMMITTEE ON APPLICATIONS TO IRON AND STEEL*

*To the Board of Directors:*

Your committee is pleased to present the following statement covering the progress of development in applications in the Iron and Steel Industry during the year ending July 31, 1928.

Constantly during this period the iron and steel industry has added to its general electrical equipment. These general additions have been towards modernizing of existing installations quite as much as anything, and all effort is directed steadily towards reduction in production costs by addition of improved machinery.

The tendency to increase blast furnace equipment is not present and this may be said to be true generally of the fundamental processes of smelting iron ore, in coverting iron into steel or in rolling the steel into the primary shapes. Such electrical additions as have been made in the foregoing are in the nature of changes of older equipment to modern.

The principal interest during the current term has been in the finished product mills which we shall term the secondary mills.

Predominant in this regard are installations in strip mills and in cold rolling, these electrical installations being modern and recording definite advance in the production of hot strip steel and in cold rolled strip.

Close regulation of the mill drive is required and to give this, motors and control have been developed and installed. Micrometric adjustment of the rolls has been obtained through motors and control specially designed for the purpose. The reeling of the strip steel has been accomplished automatically by mechanical tools, electrically driven and controlled. This accomplishment marks a definite advance in the production of perfect strip steel.

Steady improvement in detail of motors and control for such service is shown in the apparatus installed, and this is marked rather than any positively new product of our industry.

Throughout the term your committee has kept in touch with the proceedings and personnel of the Association of Iron and Steel Electrical Engineers. It has been our purpose to help the Association as we may and its proceedings again are referred to the Institute as the most complete record available of developments electrically in the Iron and Steel Industry.

In conclusion, your committee commends the plan of keeping continually in touch with the Association of Iron and Steel Electrical Engineers, giving it service wherever possible and bringing to the Institute its reports and findings, with suitable recognition. Your committee just concluding its services takes this means of acknowledging and expressing its appreciation of the assistance rendered by these reports for the current term, as well as by the constant contact with representatives of the Association.

A. G. PIERCE, *Chairman.*

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*APPLICATIONS TO IRON AND STEEL PRODUCTION:

A. G. Pierce, Chairman,

| | | |
|---|---|---|
| A. C. Bunker, | S. L. Henderson, | F. O. Schnure, |
| F. B. Crosby, | O. Needham, | J. W. Speer, |
| A. C. Cummings, | A. G. Place, | G. E. Stoltz, |
| M. M. Fowler, | | T. S. Towle, |

# High-Speed Circuit Breakers

J. W. McNAIRY*
Associate, A. I. E. E.

*Synopsis.—High-speed circuit breakers have been successfully applied to d-c. railway systems for a number of years, but designs suitable for application on 12,000-volt single-phase systems have not been available until recently.*

*A description of an air circuit breaker design suitable for 12,000-volt applications and having a speed of operation comparable with the d-c. type has been included.*

*The method of applying the magnetic type of mechanism previously used for d-c. breakers to the a-c. type breaker has been described. The theory of the operation of the saturated transformer type of trip circuit used for this purpose has been given.*

*Typical oscillograms of short circuit tests showing the high speed of operation on a-c. circuits are included.*

*The method of obtaining selective operation in connection with railway feeder circuits has also been outlined.*

*The use of this type of breaker on a 12,000-volt single-phase system makes possible the same degree of protection and selective operation as is now being realized on d-c. systems.*

## I. Introduction

HIGH-SPEED circuit breakers were first applied on d-c. railway systems for the protection of commutating apparatus against the effects of short circuits or flashover. Later development led to their application to all of the power circuits of this type of system. A paper describing the principal features of a complete breaker installation of this type on the d-c. terminal electrification of the Illinois Central R. R., Chicago, was presented at the June 20, 1926 meeting of the A. I. E. E.† Reference was made at that time to the development work being carried on in connection with a-c. applications.

The higher voltages of the trolley network of the usual a-c. system make high speed operation of circuit breakers more difficult and progress has, therefore, not been as rapid as with the d-c. type. Some applications to railway feeders of a-c. breakers designed to operate considerably faster than the usual oil breaker, have been made in the past, but speeds approaching that of the d-c. breaker have only recently been attained.

Both oil and air break types having a speed of operation comparable with the d-c. type have recently been developed and commercial designs suitable for a-c. voltages up to 12,000 volts are now available.

The application of an air circuit breaker to this type of service marks the first application of breakers of the air type to moderately high a-c. voltages.

## II. Advantages of High-Speed Operation on A-c. Railway Circuits

Short circuits are necessarily more frequent on railway systems than on other types of power distribution networks, because of the nature of the service. High-speed operation of the protecting breakers for single-phase a-c. systems reduces the effects of short circuit stresses on transformer and generator windings and limits burning of insulators, conductors, or parts of motive equipment from arcs resulting from these short circuits, in the same manner as on d-c. applications. Breakers of this type are frequently effective in preventing the burning off of trolley wires in case of an insulator, arc-over thereby minimizing delays in service from this source.

One of the most important problems in connection with a-c. railway electrifications is that of inductive interference with adjacent communication and signal circuits under short circuit conditions. The low impedance of the grounded track return circuit results in a maximum current in case of failures of the trolley circuit, and the ground current is, therefore, usually limited only by the impedance of these metallic conductors. The railway circuit differs in this respect from the usual power circuits where there is no ground metallic return circuit. Induced voltages in adjacent low voltage circuits are therefore, on the average, higher and appear more frequently than in regions where ordinary power distribution networks are located.

It is expected that the application of high speed breakers to the a-c. railway system will greatly reduce this interference by reducing to a minimum the duration of induced voltages in the parallel circuits. The reduction in the duration of the induced voltage minimizes the duty on protective devices in the communication circuits and it is expected that the false operation of relays, bells, and other devices, resulting from this induced voltage will be eliminated to a great extent. This is, perhaps, one of the greatest benefits to be derived from the application of this type of circuit breaker to the a-c. railway feeder.

## III. Speed of Operation

The total time required for the operation of the usual a-c. circuit breaker may be divided as follows: 1, time required for relay operation, 2, time required for the separation of contacts, and 3, time required for extinguishing the arc.

In some forms of breakers, particularly those the subject of this paper, the relays have been eliminated, the circuit breaker being operated directly by the short circuit current.

The speed of operation of the mechanism is more or

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*Railway Equipment Engg. Dept., General Electric Co., Erie, Pa.

†A. I. E. E. Trans., Vol. XLV, 1926, p. 962.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

less definitely fixed by the mechanics of the device and separation of the contacts occurs at a definite time after the trip point is exceeded.

For a-c. applications, the preferred breaker is one which opens the circuit at the normal zero point of the current wave, thereby avoiding undesirable voltage transients. Since separation of the contacts may occur at any instantaneous current value depending upon the magnitude of the short circuit current and the displacement of this current wave, the arc extinguishing system should be so proportioned that the current will not be forced down too rapidly before a normal zero point is reached.

This is usually not difficult since at zero current no energy is delivered to the arc and it is most easily extinguished at this point. It is possible, however, to design high speed breakers having too powerful a blowout or current rupturing system so that when the first short circuit current loop approaches a cycle in duration, and the contacts open when the line current is near the peak of the wave, the circuit may be opened too rapidly and undesirable transient voltages may result.

It is sometimes assumed that most failures on a single-phase 12,000-volt system occur at the peak of the voltage wave and, therefore, the usual short circuit is symmetrical with a duration of a normal half cycle for the first current loop. A great many short circuits, however, are produced mechanically, the conductors coming together so that the short circuit is established at any point on the voltage wave. Records obtained during experimental investigations using contacts in both air and oil for applying short circuits at 12,000 volts show transients having all degrees of displacement of the current wave.

The duration of the first loop of current is, therefore, frequently less than one-half of a normal cycle. The magnitude of the current of such a first loop is not a fair indication of the severity of the short circuit and the breaker does not receive full tripping current or current through the blow-out system until after the second current loop is reached.

The design of a breaker to limit all short circuits to a single loop of current, therefore, is difficult and if successful, the relatively powerful current rupturing system might reduce the current at a dangerous rate when the first loop approaches a cycle in duration.

It therefore appears that the most logical design of an a-c. breaker is one capable of opening heavy short circuits at the first zero after a current loop having a duration of one-half a normal cycle or longer.

## IV. OIL VS. AIR TYPE BREAKERS

One method of obtaining high speed operation is greatly to increase the mechanical speed of the conventional type of oil breaker so that sufficient arc length is obtained in the specified time for the interruption. This means the exertion of relatively great operating forces either by powerful springs or solenoids with a corresponding increase in the mechanical difficulties in starting or stopping the mechanism.

One of the most effective means of rapidly increasing the arc length is by means of the magnetic blow-out. By properly directing the forces exerted on an arc stream drawn between contacts of a circuit breaker by the fields of the blow-out coils, the arc can be lengthened at almost any desired rate. The contacts of the breaker therefore need only be separated sufficiently to stand the voltage as the circuit is opened by the collapse of the arc stream. By applying the magnetic blow-out to an oil breaker, the necessary contact separation at the instant the circuit is interrupted can be greatly reduced and a mechanism moving at moderate speeds can be utilized.

The speed of operation and rupturing capacity of experimental switches of this type have met expectations.

Elimination of oil, however, is always desirable where possible. This is particularly true for railway applications.

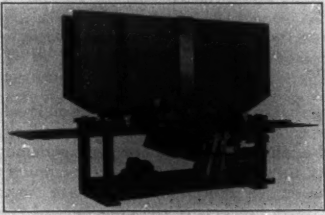


FIG. 1—12,000-VOLT, 1500-AMPERE A-C. AIR HIGH-SPEED CIRCUIT BREAKER WITHOUT OUT-DOOR HOUSING

The feeder network of important sections of electrified railway systems where continuity of power supply is imperative, requires a relatively large number of breakers for proper sectionalizing. On four-track systems of this type, the 12,000-volt breakers may average as high as two per mile and the maintenance of such a large number is obviously an important item in the operating expense.

Exposure of current carrying conductors of the railway network to the wear and tear of current collectors, in addition to conditions common to all aerial conductors results in frequent short circuits. The majority of these failures are to ground, which in railway circuits means a line to line short, the current being limited by circuit reactance only. Railway circuit breakers are therefore frequently called upon to open heavy short circuits.

The effect of repeated interruptions on oil circuit breakers is well known. If a given circuit breaker is called upon to open a circuit repeatedly without attention, the oil deteriorates to such an extent as to endanger the reliability of the breaker. Repeated short circuits are most likely to occur during bad weather conditions when filtration or changing of the oil is most difficult, particularly in outdoor installations. The air breaker is therefore much to be preferred for this type of service, assuming that it is the equivalent of the oil breaker in all other respects.

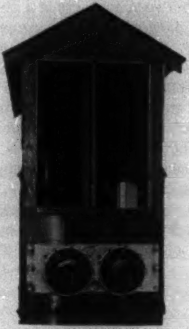


FIG. 2A—HIGH-SPEED AIR CIRCUIT BREAKER IN OUT-DOOR HOUSE WITH ONE END REMOVED TO SHOW LOCATION OF CIRCUIT BREAKER. ALSO SHOWS LOCATION OF HIGH-VOLTAGE TERMINALS

The d-c. air break circuit breaker has demonstrated its ability to withstand repeated short circuits without deterioration or objectionable damage to contacts. A-c. air break breakers of the same general type have, during experimental investigations, withstood 20 or more maximum short circuits repeated at two minute intervals without requiring attention or without deterioration of the current rupturing ability, and are on a par with the d-c. type in this respect.

FIG. 2B—12,000-VOLT, 1500-AMPERE HIGH-SPEED AIR CIRCUIT BREAKER COMPLETE WITH OUT-DOOR PROTECTIVE HOUSING OPENING 24,000 AMPERES AT 14,000 VOLTS. OSCILLOGRAM OF TEST SHOWN ON FIG. 6

On the other hand there is this to be said against the air circuit breaker:

1. The air breaker proper is not suitable for outdoor mounting and a protective housing is necessary. An air breaker complete with self-contained housing suitable for outdoor installations, is shown on Fig. 2. Fig. 2B was taken by leaving the photographic plate exposed while the breaker was opening a 24,000-ampere, 12,000-volt short circuit, the oscillogram of which is shown in Fig. 6.

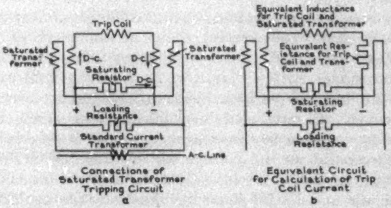
2. The operation of the circuit breaker on heavy short circuits makes somewhat more noise than the oil type.

3. The application of the air breaker is at present limited to the moderately high a-c. voltages.

Both types of breakers will, therefore, undoubtedly find a field of application on a-c. railway feeder circuits.

## V. MAGNETIC OPERATING MECHANISM

Practically all d-c. high speed breakers are of the magnetic tripping type, most designs making use of a flux shifting principle, where the flux is shifted from a holding armature to a magnetic by-pass circuit to release the breaker. The principle of operation of the flux shifting type is well known and has been described repeatedly in publications.* Briefly, it consists of a holding magnet energized by a d-c. coil across the poles of which a holding armature is bridged. Between the poles a tripping coil is introduced in such a way that when a current of proper polarity is applied the flux is shifted instantaneously from the armature to the core of the tripping coil, thereby releasing the breaker. This type of mechanism, when tripped under short circuit conditions by the line current, provides practically instantaneous release by eliminating tripping relays, a very effective arrangement when maximum speed is desired. This mechanism has been successfully applied to both oil and air type 12,000-volt a-c. breakers.



Connections of Saturated Transformer Tripping Circuit
a

Equivalent Circuit for Calculation of Trip Coil Current
b

FIG. 3—CONNECTIONS OF THE TRIPPING CIRCUIT FOR THE MAGNETIC TYPE OF A-C. HIGH-SPEED CIRCUIT BREAKER

Some means of providing a unidirectional current in the tripping coil of this type of mechanism is essential for applications on a-c. circuits. The saturated current transformer type of trip circuit was adopted for this purpose, Fig. 3. The tripping circuit is usually designed for current of 5 amperes so that standard current transformers can be used in the main power circuit.

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*Tritle, U. S. Reissue Patent 15,441.

"New Type of High Speed Circuit Breaker," by J. F. Tritle, *G. E. Review*, Vol. XXIII, p. 286.

The operation of this trip circuit perhaps may be better understood by first considering the phenomena responsible for the so-called "starting current" when voltage of proper polarity is suddenly applied to a transformer, the core of which is magnetized by residual flux. The "starting current" for the transformer is the result of lowered reactance because of over-saturation of the core, the available range in flux in one direction having been reduced because of the initial residual flux.

The transformers used in the tripping circuit are of normal current transformer design. When there is no alternating current through the windings, the flux in the cores of these transformers is maintained near the saturation point by direct current through one of the windings of each transformer, this current being the same as that used for the holding coil of the circuit breaker.

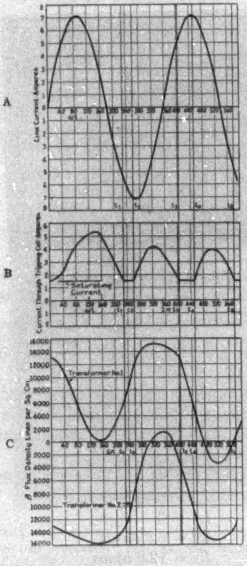

FIG. 4—CALCULATED CURRENT AND FLUX CURVES FOR SATURATED TRIPPING TRANSFORMERS USED IN CONNECTION WITH THE MAGNETIC TYPE OF MECHANISM OF THE A-C. HIGH-SPEED CIRCUIT BREAKERS

The connections are such that when current of given direction is passed through the primary winding of both transformers, such as during the first half cycle of an a-c. short circuit, it exerts a m. m. f. to increase the flux in the core of one transformer and decrease the flux of the other transformer simultaneously.

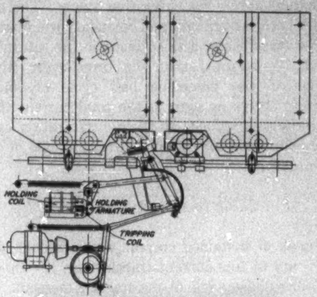

FIG. 5—OPERATING MECHANISM OF THE AIR BREAK 12,000-VOLT A-C. HIGH-SPEED CIRCUIT BREAKER

Since the cores of both transformers are initially saturated in opposite directions, the decreasing flux in one transformer generates a secondary voltage whereas the transformer in which the flux is increasing generates only a slight secondary voltage because of saturation in the core. The secondary voltages of the two transformers are connected in opposition around the tripping coil circuit and the resultant unbalanced voltage circulates current around the circuit formed by the trip coil, transformers, and resistors as shown by the current curve of Fig. 4b.

No matter what the direction of the primary current, one transformer will be active on the first half cycle, the polarities being such that the current impulse through the trip coil is always in the same direction. The phenomenon is transient and the unidirectional current is not maintained under steady state conditions.

This arrangement does not provide a steady overload trip point so that standard types of overcurrent relays are usually provided for this purpose. The high speed trip functions only in case of short circuit or heavy overload which results in a suddenly increasing line current.

Any of the usual types of relay protective systems may be used in conjunction with the high speed trip.

In an endeavor to provide a more complete explanation of the operation of these saturated transformers, the following analysis is offered:

The performance of the transformers is affected by magnetic hysteresis in the iron core. The following analysis is intended mainly as an indication of the factors affecting the performance of these transformers and hysteresis effects have therefore been ignored for the sake of simplicity. The following assumptions were also made for the same reason.

1. The transformer which is active for a given direction of primary current is assumed to hold its ratio from the instant the flux is started down, that is, the exciting current is assumed to be negligible.

2. The inductance of the transformer which is inactive because of saturation has been assumed to be constant above the saturation value. The current through both the primary and secondary windings of the inactive transformer acts to increase the saturation.

3. It is assumed that the transformer which is inactive on the preceding half cycle becomes immediately active as soon as the total current through the windings is reduced to the d-c. saturation value.

The expression for the line current in case of an a-c. short circuit is

$$I = I_M \sin(\omega t - \gamma) + I_M \sin \gamma \, \epsilon^{-\frac{t}{T}} \tag{1}$$

where

$I_M$ = peak of sustained current wave, through secondary of line current transformer, $t$ = time

$\gamma$ = time phase angle of the starting moment

$\epsilon$ = 2.718

The following symbols are employed.

$L_1$ = total inductance of trip coil circuit (saturated transformers and tripping coil)

$R_1$ = total resistance of trip coil circuit

$L_2$ = total inductance of loading circuit, Fig. 3

$R_2$ = total resistance of loading circuit, Fig. 3

$I$ = total current in secondary of line current transformer

$i_1$ = current through trip coil

$i_2$ = current through loading circuit

$\omega$ = $2\pi f$

$t$ = time in seconds

$T$ = time constant of main power circuit.

The equivalent circuit for the period during which a current impulse is passing through the tripping coil is shown by Fig. 3B.

The current through the tripping coil of the circuit breaker is determined as follows:

One to one ratio; saturated transformers are considered. The fundamental differential equation for the circuit is

$$R_1 i_1 + L_1 \frac{d i_1}{d t} = R_2 i_2 + L_2 \frac{d i_2}{d t} \tag{2}$$

also

$$I = i_1 + i_2 \tag{3}$$

$$\frac{d I}{d t} = \frac{d i_1}{d t} + \frac{d i_2}{d t} \tag{4}$$

substituting (1) in (2) and eliminating $i_2$ terms

$$(R_1 + R_2) i_1 + (L_1 + L_2) \frac{d i_1}{d t} = I_m \Big[ R_2 \sin(\omega t - \gamma) + R_2 \sin \gamma \, e^{-\frac{t}{T}} + L_2 \, \omega \cos(\omega t - \gamma) + \frac{L_2}{T} \sin \gamma \, e^{-\frac{t}{T}} \Big] \tag{5}$$

which is integrated for $i_1$

$$i_1 = I_M \Bigg[ \left( \frac{R_2(R_1+R_2) + \omega^2 L_2(L_1+L_2)}{(R_1 + R_2)^2 + (L_1 + L_2)^2 \omega^2} \right) \sin(\omega t - \gamma) + \left( \frac{\omega L_2 (R_1 + R_2) - R_2 \, \omega (L_1 + L_2)}{(R_1 + R_2) + (L_1 + L_2)^2 \omega^2} \right) \cos(\omega t - \gamma) + \left( \frac{(R_2 T + L_2) \sin \gamma}{T(R_1 + R_2) - (L_1 + L_2)} \right) e^{-\frac{t}{T}} + C e^{-\left(\frac{R_1 + R_2}{L_1 + L_2}\right) t} \Bigg] \tag{6}$$

The above relation holds only during the period when one transformer is active and the other inactive.

The magnetic trip circuit is sufficiently responsive to trip on instantaneous current values, the armature being released if the current through the trip coil exceeds the setting during the peak of an a-c. wave. The breaker is therefore released on the first current impulse which exceeds the trip point and the determination of the first tripping impulse is most important in connection with breaker performance.

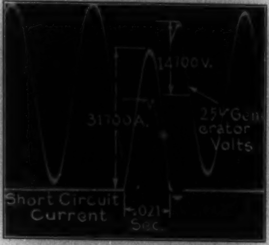

FIG. 6—OSCILLOGRAM OF "OCO" SHORT CIRCUIT TEST AT 14,000 VOLTS, 24,000 AMPERES, R. M. S. ON 12,000-VOLT AIR CIRCUIT BREAKER

The current through the trip coil of the circuit breaker for a symmetrical short circuit namely with $\gamma = 0$ has been calculated for a typical case using equation (6) as follows:

The constants of the circuits involved are as follows:

$L_1$ = 0.11 henrys
$L_2$ = 0
$R_1$ = 5.6 ohms
$R_2$ = 12.0 ohms
$T$ = 0.00625
$I_M$ = 7.1 amperes

Referring to Fig. 3a the resistance of the saturating resistor is made the same as the total resistance of tripping coil and transformer secondary windings and the steady direct current supplied to this circuit for saturating the transformers divides equally between the two parallel paths.

The resultant d-c. voltage drop produced by this current in the parallel paths is equal and opposite around the circuit through which the tripping current circulates and therefore does not enter into the determination of the tripping current with the exception that the current value obtained from equation (**6**) is superimposed on the d-c. saturating current as shown by Fig. 4b.

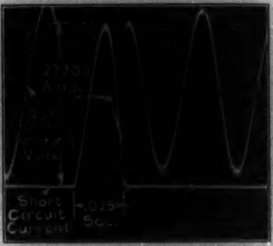

Fig. 7—Oscillogram of "OCO" Short Circuit Test at 12,000 Volts, 22,000 Amperes R. M. S. on 12,000-Volt Air Circuit Breaker

The integration constant $C$ is therefore determined by the initial conditions $t = 0$ $i_1 = 0$ and the expression $i_1$ for the first loop of current (Fig. 4b) is found to be

$$i_1 = I_M\,[.348 \sin \omega t - .342 \cos \omega t + .342\, e^{-160t}] \qquad (7)$$

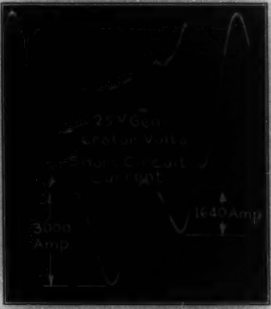

Fig. 8—Oscillogram of 12,000-Volt, 2700-Ampere R. M. S Short Circuit Test on Air High-Speed Circuit Breaker

The voltage can be found by differentiating (**7**) for $\dfrac{d\,i_1}{d\,t}$ and substituting this and (**7**) in

$$E = i_1 R + L_1 \frac{d\,i_1}{d\,t}$$

for the case under consideration.

$$E = I_M\,[7.858 \sin \omega t + 4.105 \cos \omega t - 4.105\, e^{-160t}] \qquad (8)$$

The flux of the active transformer is determined from

$$E = 10^{-8}\, I_m\, N\, A\, \frac{d\,\Phi}{d\,t}$$

$$= [7.858 \sin \omega t + 4.105 \cos \omega t - 4.105\, e^{-160t}] \qquad (9)$$

Where $N$ = number of turns on transformer secondary
$A$ = area of core sq. cm.

$$\Phi = \frac{10^8\, I_M}{N\,A}\,[\,.0262 \sin \omega t - .0502 \cos \omega t + .0257\, e^{-160t} + C] \qquad (10)$$

the initial flux is maintained at 13,000 lines per sq. cm. by the saturating direct current, therefore for

$$T = 0 \quad \Phi_0 = 13{,}000 = \frac{10^8\, I_M}{N\,A}\,[-\,.0502 + .0257 + C] \qquad (11)$$

and

$$C = -\,.0245$$

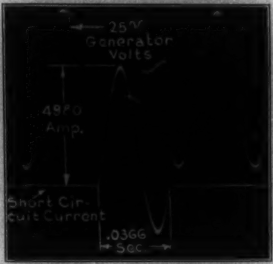

Fig. 9—Oscillogram of a 3700 Ampere R. M. S. 12,000-Volt Short Circuit Test on an Air Break Circuit Breaker

The flux curve calculated from (**10**) is shown by Fig. 4c.

It will be noted that at the time $t_1$ the current through the windings of the inactive transformer is reduced to the d-c. saturating current value, as the line current continues to increase during the second one-half cycle and a voltage is induced in the secondary winding of this transformer. From the flux curve of Fig. 4c, however, it will be seen that the flux of the previously active transformer has not yet returned to the saturation value and therefore there is a period from $t_1$ to $t_2$ where both transformers are active and present full transformer reactance to the flow of current and the total line current therefore flows through resistance $R_2$, (ignoring the exciting current for the transformers).

The flux change in both transformers for the period $t_1 - t_2$ is therefore determined by the voltage across the loading resistor $R_2$, Fig. 3a.

$$V = 10^{-8}\, I_M\, R_2\, N\, A\, \frac{d\,\Phi}{d\,t} = I_M \sin \omega t$$

$$\Phi = \frac{12 \times 10^8}{N\,A}\,[-\cos \omega t]$$

The corresponding flux curves for the period $t_1$ to $t_2$ until the flux of transformer No. 1 again reaches the saturation point, is shown on 4c. After saturation is reached, in the case of No. 1 transformer, a second current impulse is passed through the trip coil circuit by No. 2 transformer, the method of determination being the same as for the first impulse. At the conclusion of the second impulse, $t_3$, the flux of the second transformer is further from the saturation value than was the flux of No. 1 transformer at the end of the first loop and the line current again passes through $R_2$ until saturation is reached, the period from $t_3$ to $t_4$ being correspondingly greater than the period from $t_1$ to $t_2$.

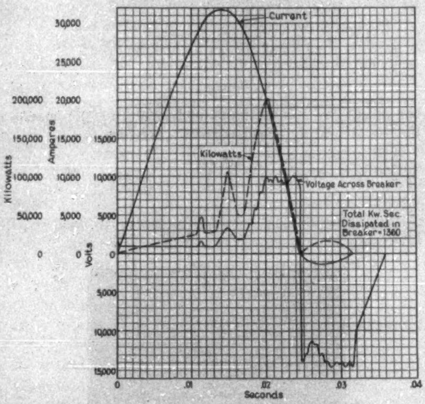

FIG. 10—CURVE TAKEN FROM OSCILLOGRAM FIG. 6, SHOWING KILOWATTS DISSIPATED IN THE ARC CHUTE OF AIR CIRCUIT BREAKER DURING A SHORT CIRCUIT TEST AT 14,000 VOLTS

In this manner the process is repeated, the period in which both transformers are active growing longer with each succeeding half cycle until a stable condition is reached where the flux is increasing through one transformer and decreasing through the other transformer for the full one-half cycle. When this occurs the sustained condition has been reached and no further current impulses are supplied to the trip coil so long as the line current is not increased. The full line current under steady state conditions passes through the resistance $R_2$.

The trip current supplied by this tripping circuit is approximately proportional to the increase in line current. Typical oscillograms showing the tripping current are shown on Fig. 11. The oscillograms of Fig. 11 were taken when applying an overload to the circuit which was previously carrying a steady load. The saturating current in this case was passed through an independent winding on the saturated transformers.

After the steady state condition is reached, should the line current be suddenly increased again, the saturation point is reached on one transformer as soon as the line current exceeds the steady state value and further current impulses are supplied through the tripping coil circuit.

## VI. DESCRIPTION OF THE AIR BREAK CIRCUIT BREAKER

Photographs of a 12,000-volt 1500-ampere single-phase air break circuit breaker are shown on Figs. 1 and 2. A drawing of the principal parts of the mechanism is shown in Fig. 5. The armature, which is held in the closed position by a holding coil and released by a wire wound trip coil inserted between the poles of the holding magnet, is shown connected to the main high voltage contact arm through insulated pull rods.

The high voltage contact arms are operated entirely through suitable insulating pull rods, the mechanism being grounded. The circuit breaker as a whole consists of two sets of contacts and arc chutes which are connected in series, the moving contact arms being connected together by a suitable bus so that they form in effect a bridging contact similar to that used in oil circuit breakers.

There are two sets of springs, the main springs operating directly on the armature for opening at high speed while the contact pressure is exerted by a second set attached to the pull rods at the bottom of the arm.

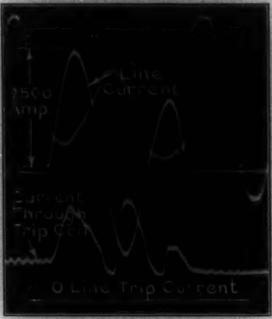

FIG. 11—TYPICAL OSCILLOGRAMS SHOWING CURRENT OBTAINED WITH SATURATED TRANSFORMER TRIPPING CIRCUIT FOR MAGNETIC TYPE OF HIGH-SPEED A-C. CIRCUIT BREAKER

This mechanism is inherently trip free, the operation being as follows:

Resetting is accomplished by means of a motor-operated cam. The first movement of the cam operates the lever attached to the pull rods at the bottom of the contact arms rotating these arms about the top bumper as a fulcrum. The holding armature is pulled to the closed position by the main pull rods attached between the center of the contact arms and the bell cranks on the armature shaft. This armature is latched as the peak of the cam is reached without reducing the gap between contacts. Further movement of the cam allows the bottom springs to rotate the contact arm to the closed position around the top pull rods as a center.

The bottom of the arms when opening on short circuits, is held approximately stationary when opening by the weight of parts attached to the bottom. In the event the breaker is closed on a short circuit the mechanism therefore operates the contact at full speed regardless of the fact that the rollers have not yet left the cam surface.

The high voltage circuit through the breaker is very direct, entering on one side through series blow-out coils, one end of which is connected to a stationary contact. The circuit is completed through the moving contact and arm and another set of series blow-out coils from which the connection is made to the second contact mechanism, a duplicate of the first.

When the contacts separate under short circuit conditions, the arc is drawn on the arcing horns and detached blow-out coils are cut in successively as the arc travels along these horns. The general arrangement of the blow-out coils, arc suppressor plates, arcing horns, etc., is the same as that used on standard designs of 3000-volt d-c. breakers with the exception that a greater number of blow-out coils is used and the arc chutes are designed to permit a considerably longer arc.

A new feature which is introduced in this breaker consists of high resistance arcing horns made from a special material and designed to absorb a considerable voltage as the arc is forced along them under the action of blow-out coils. These arcing horns are effective in reducing the energy in the arc stream and in reducing the flame and noise of the breaker when opening under short circuit conditions.

Some typical oscillograms obtained during short circuit tests, including tests at 14,000 volts single phase, 25 cycle are shown in Figs. 6 to 9 included. The curves on Fig. 10 were plotted to show the current, voltage, and power relations during a short circuit test of 14,000 volts. It is interesting to note that the energy is liberated in the arc chute at a maximum rate of 200,000 kw.

The speed of operation of the mechanism taken with a mechanical speed recorder is shown by the curve on Fig. 12. It will be noted that total tip gap of more than 6 in. (two contacts in series) is reached in slightly more than the time required for a normal ½ cycle (25 cycle) after the trip point is exceeded.

## VII. Current Rupturing Tests on Air Breaker

This breaker has successfully opened a current of 24,000 amperes r. m. s. at 14,000 volts repeatedly. A series of 20 OCO tests at 12,000 volts, 22,000 amperes, r. m. s. was made at two-minute intervals without examination or attention of any kind to the circuit breaker. A single contact and arc chute of this type of breaker, equivalent to one-half the standard 12,000-volt breaker has opened a maximum current of 41,000 amperes r. m. s. at 7000 volts repeatedly, both the tests at 14,000 and 7000 volts being the maximum available at the time the tests were conducted.

## VIII. Selective Operation of the High Speed A-C. Breaker

Selective operation of high speed a-c. breakers applied to railway feeders is essential. The high-speed feeder breakers should isolate defective feeder sections between substations without disturbing power flow to adjacent interconnected sections under all short circuit conditions.

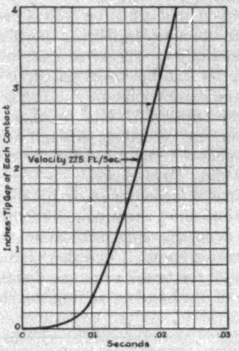

Fig. 12—Mechanical Speed of 12,000-Volt Air High-Speed Circuit Breaker

The connections shown in Fig. 13 are utilized for obtaining selective operation where the unidirectional current impulse type of trip is used. Advantage is taken of the unidirectional trip circuit in a differential connection. The tripping circuits of all breakers are connected to a common bus in such a way that the trip current circulating through any trip coil must return either through the trip coils of parallel breakers or the saturating resistor indicated on the diagram. When the current is increased simultaneously through all breakers feeding the feeders in a given direction from the substation, the tripping current for all of these breakers must pass through the saturating resistor shown on the diagram, since equal voltages are generated by the trip circuits of each breaker. The current required for tripping all of the circuit breakers under this condition is much higher than when the current is increased through one breaker only. By selecting a proper value for the saturating resistor the current necessary for operation with a simultaneous current increase through all breakers can be made higher than the exchange current over the trolleys between substations in case of internal short circuit in one substation.

If the current is suddenly increased in one breaker only, by a short circuit on one feeder, tripping current is supplied to the breaker supplying the faulty feeder, this current returning through the coils of the remaining breakers and assisting to hold them closed. The tripping current for the breaker involved is considerably less than when all breakers carry current because of the lower impedance of the return circuit for the tripping current.

A simplified diagram showing breakers located in a typical feeder network has been shown in Fig. 14.

The operation of the breakers under typical short circuit conditions with connections as shown in Fig. 13 is as follows:

1. *Feeder Short Circuits.*

In the event of a short circuit on a feeder between substations, the breaker supplying this feeder carries a current considerably in excess of that of the parallel breakers since the parallel breakers carry the exchange current between substations only. Tripping current is supplied to the trip coil of this breaker, operating it, some of this current returning through the trip coils of the parallel breakers in reverse direction for tripping and assisting in holding them closed.

In the event of a feeder short circuit directly in front of one substation, all of the breakers in the distant substation carry equal currents until after the breaker in the near substation opens. The short circuit current is removed from all the breakers at the distant station by the operation of the breaker feeding the short directly, except the distant breaker feeding the faulty trolley. The current through this breaker is suddenly increased because of the removal of the heavy short circuit current from the high voltage transmission line and this breaker is operated, clearing the remaining short circuit.

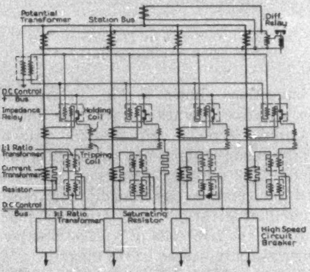

FIG. 13—DIFFERENTIAL CIRCUIT FOR SELECTIVE OPERATION OF FOUR MAGNETIC TYPE HIGH-SPEED CIRCUIT BREAKERS APPLIED TO A 12,000-VOLT TROLLEY FEEDER NETWORK

2. *Substation Bus Short Circuit.*

In the event a short circuit occurs on the bus at a given substation, all breakers interconnecting the two substations carry equal exchange currents. These breakers are, therefore, not operated by the high speed trip and the bus is isolated by the operation of a standard type of differential relay which opens all of the breakers connected to this bus. The feeders between substations are fed from the distant station and are not deenergized.

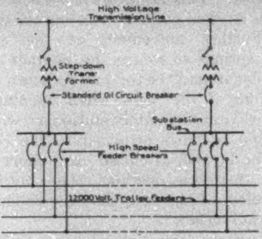
High Voltage Transmission Line
Step-down Transformer
Standard Oil Circuit Breaker
Substation Bus
High Speed Feeder Breakers
12000 Volt Trolley Feeders

FIG. 14—SIMPLIFIED DIAGRAM OF A TYPICAL HIGH-SPEED BREAKER INSTALLATION ON A 12,000-VOLT RAILWAY FEEDER NETWORK

3. In case a short circuit occurs in the stepdown transformer or in the high tension line, the feeder breakers between the faulty substation and adjacent substation carry equal exchange currents and therefore do not receive a sufficiently high tripping current to operate. The faulty transformer or high voltage line is disconnected from the bus by the operation of a standard differential relay around the transformer or reverse power relays in case of a high voltage line short, both of which operate a circuit breaker on the low voltage side of the transformer.

## CONCLUSION

The development of both air break and oil break 12,000-volt a-c. high-speed circuit breakers having a speed of operation comparable with the d-c. type makes possible the same degree of selectivity and protection on a-c. electrified systems as has been obtained for a number of years on equivalent d-c. systems.

It is expected that this type of breaker will be particularly beneficial in minimizing inductive interference in signal and communication circuits.

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## Discussion

For discussion of this paper see page 1311.

# High-Speed Circuit Breakers for Railway Electrification

## From the Design Point of View

BY H. M. WILCOX[1]

Member, A. I. E. E.

FROM the point of view of switching service, circuit breakers as a whole may be divided roughly into general classifications dependent on the time required to isolate portions of the circuit under conditions of fault or to clear the circuit under any predetermined condition. Of these, the conventional normal-speed breaker constitutes by far the largest class in general use.

For d-c. switching service, this class is generally of the carbon-break type often applied in machine circuits with relatively high normal current loads requiring breakers of large current-carrying capacity with heavy moving elements. These breakers may be expected to interrupt a short circuit in from 0.07 to 0.10 sec. from the start of rise of short circuit current, although they are often used with a time-delay element intentionally placed in the control circuit to increase this time up to a full second or more. Where quicker action is desirable, particularly with breakers of lower current-carrying capacity, the contacts may be made trip-free from the closing mechanism and with a sensitive overload tripping device the time may be reduced to from 0.04 to 0.06 sec. The general form of the breaker, however, is not materially different in these two time classifications.

For a-c. switching service, the normal-speed oil circuit breaker is used over practically the entire range of service voltages. When actuated by a normal-speed relay, this breaker requires from 0.10 to 0.25 sec. after the occurrence of a fault to trip the breaker and interrupt the circuit. As in the case of the d-c. breaker, however, it is often used with a time-delay element in the control circuit extending the total time up to as much as three or four seconds. Where switching is mainly on the low side of the transformers the normal loads involved may require breakers of high current-carrying capacity with heavy moving elements, and for great concentrations of power the current rupturing requirements may be relatively high, calling for substantial sturdy construction of the contact details. When switching at higher voltages, the current loads become proportionately less, making lighter contacts feasible, and various forms of high speed contacts are used in which contact is maintained between arcing tips in the breaker until the main moving element has completed a considerable portion of its opening movement. The arcing tips are then snapped open at a high rate of speed independent of the speed of the main moving element, thus materially decreasing the duration of arcing. High-speed relaying is also resorted to where it becomes desirable to diminish the time between the occurrence of a fault and the drawing of an arc at the breaker contacts. In all of these forms, however, the breaker structures differ only in details and they may all be included in the same general classification.

During the last few years, the rapid advance in railway electrification work, particularly in the application of automatic features, has resulted in the development of a new class of breakers for this service known as high-speed circuit breakers. Developed largely for special protective purposes, these breakers perform a somewhat different function from that of breakers in other service for both of the two great classes of railway applications, d-c. and a-c. electrification projects. In time classification, high-speed breakers should function to interrupt a d-c. circuit in 0.02 sec. or less after the occurrence of a fault, and one cycle or less for a 25-cycle a-c. circuit.

In d-c. railway service, the synchronous converter operating at from 600 to 1500 volts occupies a commanding position as a medium for converting alternating current from the secondaries of transformers into direct current supplying feeder circuits for trolley or third rail service. This machine lends itself readily to automatic control without the necessity of an attendant, but is susceptible to flashing with considerable consequent damage to the commutating apparatus under short circuit conditions. To obviate this difficulty, the d-c. high-speed breaker has been developed to the point of interrupting a circuit before short circuit current can rise to its full value, and of so limiting the destructive period of duration of a short circuit as to preclude the possibility of flashing on the commutator. Fig. 1 shows a high-speed circuit breaker designed for 1500-volt d-c. railway service.

From the design point of view, certain characteristics must be incorporated in this breaker to meet the requirements for high-speed protection in d-c. circuits. The operating voltage for the majority of railway applications is 600, with a comparatively small number 1500 volts, so that a single break of from 1¼ to 1½ in. will be sufficient for the contacts when used in conjunction with an auxiliary magnetic blowout circuit.

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With careful attention paid to design of the contacts in order to reduce the air-gap in the blowout magnet to a minimum, a blowout value of the order of 20,000 ampere-turns at 5000 amperes will be sufficient where high-speed interruption is confined to current values of from 3000 amperes upward. For small kilowatt capacity machines, where high-speed action is desired for currents as low as 800 to 1000 amperes, blowout values must be materially increased to assure satisfactory results in operation.

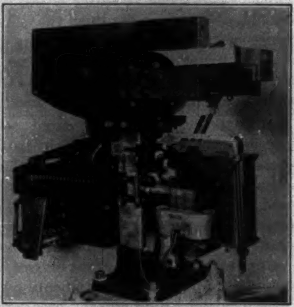

FIG. 1—HIGH-SPEED CIRCUIT BREAKER FOR 1500-VOLT D-C. RAILWAY SERVICE, CIRCUIT RATING, 3000 AMPERES

Blowout values of this order may be expected to remove an arc from the contact surfaces and transfer it to arcing horns during the first one-quarter inch of contact travel, so that all of the mechanical force applied to produce acceleration of the moving contact on opening should be concentrated so far as possible in this first one-quarter inch of travel and no further interest need attach to the speed of contact opening beyond this point except to insure that there is sufficient contact separation at the time the arc is extinguished to prevent reestablishment of the circuit. The problem then becomes one of acceleration rather than of high speed, since the accelerating force, while quite large, is not applied for a sufficiently great length of time to produce relatively high speeds. Fig. 2 shows the speed of contact travel at various points in the opening stroke up to one inch on a high-speed breaker designed for 3000 ampere d-c. service.

From this it will be apparent that for d-c. service, any feature which detracts from the amount of contact opening during the first 0.004 sec. after the breaker is tripped will hinder the limitation of current very materially. For instance, an auxiliary arcing contact with a quarter-inch lead would result in a complete loss of this time and a flexible brush contact involving an eighth-inch follow-up would result in a loss of nearly 70 per cent of it. Consequently, where feasible, a solid butt contact without auxiliary arcing tips becomes very desirable. Such a contact also permits working to a much higher current density, resulting in a very considerable reduction in the mass to be accelerated since there is no flexible laminated copper present to suffer possible deterioration under excess temperatures. Given a design in which the flexibility necessary to secure adequate contact pressure is supplied by a spring, working through leverage if necessary, the solid butt contact becomes entirely feasible for this application.

The resulting design is, then, a solid butt contact which carries main-circuit current, on which the arc is drawn as soon as mechanical separation of the contact surfaces is obtained, and from which the arc is transferred to arcing horns very early in the opening stroke by a powerful blowout magnet. These arcing horns are an integral part of the arc chute and care must be taken in the design to arrange them so as to secure the greatest possible increase in the length of arc in the shortest interval of time. Test data indicate that a d-c. arc becomes unstable at potentials in the order of 30 to 35 volts per in. of length which would require stretching a 1500-volt arc to a length of approximately 45 in. for interruption. The arc chute for a 1500-volt breaker must then be designed to accommodate an arc of this length with sufficient additional capacity to cover such overvoltages as may be encountered on highly inductive circuits without permitting the arc to extend outside of the chute to such an extent as to strike other potential points. Care must be taken also in the design of pole faces to secure a properly graduated blowout field over the arcing area. This field must be intensified at the point of origin of the arc, but must shade off rather rapidly after the length of arc has reached a point corresponding to the limitation of current rise in order that the rate of fall of current may not be too rapid as the interrupting point is approached. Tests with breakers of this type indicate that a very fast falling current may be accompanied by an overvoltage surge of such magnitude as to cause severe potential stresses on the machine. From this point of view, a breaker which interrupts a given circuit in 0.015 sec. may impose materially less stress on the machine than one which gives complete interruption in considerably less time.

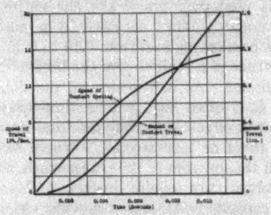

FIG. 2—SPEED OF CONTACT OPENING FOR HIGH-SPEED D-C. CIRCUIT BREAKER. CURRENT CAPACITY, 3000 AMPERES

From time to time, various arrangements of arc splitters have been incorporated in d-c. arc chutes in an attempt to supply a mechanical means of lengthening the arc rapidly. Difficulty has been encountered in the use of such splitters due to their choking the expulsion of gases from the vicinity of the contacts with consequent re-ignition of the circuit across the points of the arc splitters or across the contacts themselves. The tendency in modern breakers is toward the removal of all obstructions in the chute to permit the free action of convection currents following the rise of the arc and thus provide adequate ventilation for removing the gas field from the vicinity of the contacts as the arc extends.

As to mechanical operation of the contacts, the breaker must be capable of high-speed interruption in the event of being closed against a fault in service, which requires that it be trip-free in action. This is best accomplished by a multiple-stage closing stroke through a floating lever. Fig. 6 shows the arrangement of such a mechanism in which the closing power is applied at one end of the floating lever and utilized to seal the holding armature while the contacts remain in the open position. A set of closing springs is also extended by this closing solenoid stroke. Upon de-energizing the solenoid, these closing springs serve the threefold purpose of closing the contacts, extending the opening springs, and retrieving the solenoid core. Thus by utilizing various pin centers in the floating lever as fulcrums at different stages of the movement, the contacts become trip-free at any point in the closing stroke. The excess of power in the closing springs over that of the opening springs provides the flexible means necessary for maintaining adequate contact pressure referred to previously. While tending to maintain the contacts in the closed position, these closing springs in no way hinder the opening movement since the point at which the holding-in power is applied becomes a fulcrum for the opening movement as soon as the holding armature is released.

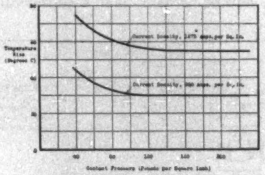

Fig. 3—Relation of Temperature Rise to Contact Pressure for Solid Butt Contacts in Air

Fig. 3 shows the effect of contact pressure on temperature rise with the use of solid butt contacts in air for current densities per square inch of contact surface of the order of magnitude ordinarily used in breakers of this type for railway service. It will be noted that the temperature rise decreases quite rapidly with the increase in pressure through the lower range but the decrease is less marked at pressures of from 80 to 100 lb. and very little improvement is shown beyond this point for pressures up to well over 200 lb. per sq. in. From these curves it will be apparent that the method of securing contact pressure by maintaining a balance between two springs may be relied upon to give adequate pressure, and at the same time provide a considerable range in adjustment of the springs for other purposes. Comparative tests have been made to determine the ability of this type of contact to carry heavy current loads after repeated drawing of arcs from the main contact surfaces. The temperature rise was determined by test for a breaker with new contacts worked at a current density of approximately 1200 amperes per sq. in. of contact surface, and a second test made on the same breaker after it had been used for short circuit test purposes until the contact surfaces showed no indication of their original machining, and without any cleaning of these surfaces. This second test showed approximately 15 per cent less current density for the same temperature rise. The contacts should, then, be designed with sufficient factor of safety to permit an equivalent increase in temperature rise before reaching final temperatures at which deterioration of the contact material may begin.

In view of the rigid requirements as to time for the operation of high-speed breakers in d-c. circuits, the delay involved in releasing a mechanical latch of the conventional type becomes a severe penalty when this device is used. An arrangement which has been found well adapted for retaining the d-c. high-speed breaker in its closed position comprises a stationary holding magnet and an armature linked to the operating levers, so arranged that upon the decay of holding flux, due either to the interruption of holding current or to demagnetization from some other source, the armature will release and permit the contacts to open under the influence of the opening springs. As the armature must be given a high rate of acceleration, its mass will be reduced as much as possible, resulting in its being worked well up toward the knee of the saturation curve.

This being a protective breaker, designed to limit the rise of short circuit current in the shortest possible interval of time after the occurrence of a fault, some form of tripping other than simply the consequence of amperes of overload becomes essential. An overload device is inherently unable to determine whether or not a load is to become a hazard until it has already reached the hazardous point, and this in the case of a short circuit of fast-rising current is far too late to limit that rise satisfactorily. A discriminating device known as an inductive shunt, whose action is based on the rate of rise of current, is best adapted to the requirements. The main power circuit in the vicinity of the holding magnet is divided into two parallel paths, one of which passes through the air-gap of the holding magnet while the second by-passes this magnet. Under conditions of steady load or of slowly-rising load, the by-pass lead carries a relatively large proportion of the current and the air-gap lead a small proportion which, due to the arrangement of potentials, produces a flux in the holding armature opposed to that generated by the holding coil current. So long as steady conditions or slowly-rising conditions obtain, the holding coil predominates and the armature holds the contacts in the closed position. The by-pass lead is, however, so arranged as to be acted upon by a laminated iron circuit which in the event of a rapid rate of rise in current acts to force a comparatively large proportion of the load through the air-gap lead momentarily. This results in a sudden increase in the demagnetizing flux in the holding armature which releases it and allows the contacts to open due to the action of the opening springs.

It will be apparent that with this arrangement, a balance may be secured between the holding coil flux and that generated by the action of the inductive shunt so sensitive as to permit the breaker to open with very slow rates of rise of main circuit current. General operating conditions in d-c. railway service, however, require that the high-speed breaker shall not open on legitimate changes in load such as the acceleration of a train, and some point just above the fastest rate of rise obtainable from train acceleration becomes the lower limit at which this breaker may be allowed to open under changing load conditions. It will be understood that in operating service a fault may occur which due to circuit conditions, generally a matter of distance from the station, gives a rate of rise of short circuit current less than the rise from nearby heavy train acceleration and that the high-speed breaker may not be expected to interrupt such short circuits when the balance between holding and demagnetizing flux is so arranged as to open only on a higher rate of rise. Some other discriminating device must be installed in the circuit for this purpose. It will also be obvious that this degree of sensitivity in the breaker may be dulled further over a wide range until the point is reached where it has become practically an overload breaker with no discriminating characteristics and with very little ability to protect a commutating machine. It should be borne in mind that where this type of breaker is applied for the performance of functions other than opening on rate of rise of current, some degree of discrimination will be sacrificed with a corresponding loss in the protective function for which it was primarily designed.

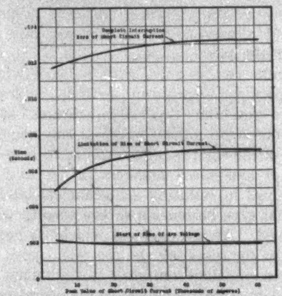

FIG. 4—TIME CHARACTERISTICS OF HIGH-SPEED D-C. CIRCUIT BREAKER ON SHORT CIRCUIT TEST, AT 600 VOLTS

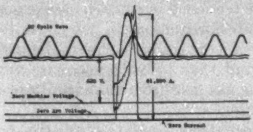

FIG. 5—OSCILLOGRAM SHOWING PERFORMANCE OF HIGH-SPEED D-C. CIRCUIT BREAKER ON OCO DUTY CYCLE

Fig. 4 shows the time characteristics of a high-speed d-c. circuit breaker over a considerable current range at 600 volts. For current rises of from five million amperes per second upward, for d-c. voltages up to 1500, these breakers may be expected to limit the rise of short circuit current in from 0.006 to 0.008 sec. and to interrupt the circuit completely in from 0.012 to 0.016 sec. Tests on a 600-volt synchronous

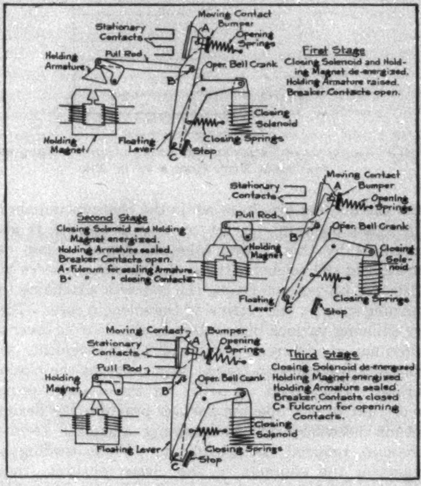
Moving Contact
Stationary Contacts
Bumper
A
Opening Springs
Pull Rod
Holding Armature
B
Oper. Bell Crank
First Stage
Closing Solenoid and Holding Magnet de-energized.
Holding Armature raised.
Breaker Contacts open.
Closing Solenoid
Closing Springs
Holding Magnet
Floating Lever
C
Stop
Moving Contact
A
Bumper
Stationary Contacts
Opening Springs
Pull Rod
B
Oper. Bell Crank
Second Stage
Closing Solenoid and Holding Magnet energized.
Holding Armature sealed.
Breaker Contacts open.
A = Fulcrum for sealing Armature.
B = " " closing Contacts.
Holding Magnet
Closing Solenoid
Floating Lever
C
Closing Springs
Stop
Moving Contact
Bumper
Stationary Contacts
A
Opening Springs
Pull Rod
Holding Magnet
B
Oper. Bell Crank
Third Stage
Closing Solenoid de-energized.
Holding Magnet energized.
Holding Armature sealed.
Breaker Contacts closed.
C = Fulcrum for opening Contacts.
Closing Solenoid
Floating Lever
Closing Springs
C
Stop

FIG. 6—DIAGRAMMATIC SKETCH SHOWING MULTI-STAGE CLOSING MECHANISM FOR HIGH-SPEED, TRIP-FREE ACTION

converter substation giving a current rise of the order of thirteen million amperes per second show limitation of short circuit current across the buses to slightly less than 300 per cent of normal load. For machines whose characteristics give a slower rate of rise such as a d-c. generator, the time of limitation and interruption of current will be proportionately longer while still providing adequate protection to the commutating apparatus. Fig. 5 is an oscillographic record of high-speed breaker performance on heavy current at 600 volts.

For alternating-current railway service, the high-speed breaker assumes an entirely different form. The majority of such applications today are main-line electrification projects fed from overhead contact lines at 11,000 volts, 25 cycles, with frequent movements of heavy trains. On such applications the use of high-speed breakers capable of limiting the duration of short-circuit current is of considerable advantage in lessening the shock to the system, in reducing the damage to contact lines, and in minimizing the possibility of synchronous machines falling out of step. Furthermore, the use of high-speed breakers facilitates the coordination of propulsion and communication circuits when they are involved in an inductive exposure. As this propulsion service is almost entirely confined to a frequency of 25 cycles, one-cycle operation allows 0.04 sec. for the detection and interruption of a short circuit. The high-speed circuit breaker shown in Fig. 7 has been developed to meet the requirements of such applications. Essentially a single-pole oil circuit breaker of the conventional gravity break type, it differs from the normal-speed oil breaker in that it carries: a high-speed shunt-tripping device; provision for a high acceleration of the moving contact; an auxiliary magnetic blowout circuit for lengthening the arc rapidly; it is actuated by a specially-designed high-speed relay. Unlike the d-c. high-speed breaker, it carries no discriminating features in itself but is actuated solely by the high-speed relay in which are incorporated all the characteristics necessary for such selectivity in tripping as may be desirable for any given application. The breaker carries a voltage rating of 15 kv., although all electrical clearances outside the interrupting chamber are adequate for 37-kv. service. It is designed for steady current loads of 1500 amperes at 25 cycles, and has an interrupting capacity of 50,000 amperes at 12 kv.

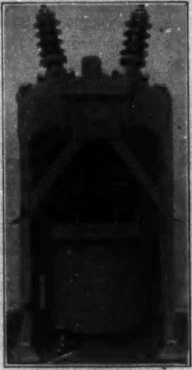

Fig. 7—Front View of High-Speed Circuit Breaker for A-c. Railway Service, Rating 15 Kv., 1500 Amperes, 25 Cycles

From the design point of view, this breaker presents a problem somewhat different from that involved in the d-c. high-speed breaker. The holding magnet raises problems due to directional characteristics when applied to a-c. circuits that require considerable in the way of added complications to overcome. Furthermore, this form of tripping does not carry inherently the degree of selectivity desirable for the majority of a-c. railway applications and some additional relaying becomes advisable when it is used. Consequently, a quick-acting mechanical latch released by a high-speed trip magnet, which in turn is actuated by a high speed selective relay external to the breaker, becomes not only feasible but desirable from the point of view of close accurate settings for selective tripping.

For like reasons the contacts in this breaker may be designed differently from those of the d-c. high-speed breaker. To perform the function for which it was developed, the breaker is placed in the contact line feeder circuits where the current loads are relatively light as compared with the heavy machine loads of d-c. railway circuits. The flexible brush form of contact may be used here without imposing great burdens in the form of mass, to be accelerated at high speed, provided the brush is used as the stationary element of the contacts. By a liberal design of this stationary element, the moving element may be worked at a comparatively high current density, depending on the stationary copper to conduct heat away, and the mass to be accelerated thus reduced to proportions that may be handled with reasonable facility.

The breaker must be trip-free in order to interrupt the circuit at high speed in the event of being closed against a fault. In the conventional form of oil circuit breaker the trip-free point is normally placed at the closing mechanism in order to combine the closing and tripping features in a single unit and to insure simultaneous action in all phases of a multiple-pole breaker. In this country at the present time, a-c. railway applications are, however, practically all on a single-phase basis so that a single-pole breaker meets all requirements. The trip-free point may then be placed as close to the moving contact element as mechanical and electrical requirements will permit, provided the tripping mechanism is placed at this point also. The point best suited to all these conditions will be found at the upper end of the contact lift rod, requiring only the contact, its lift rod, and one lever to be accelerated on opening. The accelerating force may be supplied by a helical spring concentric with the lift rod.

Fig. 8 shows in graphic form the accelerating force in pounds for each pound of mass accelerated necessary to produce various speeds at the end of the first one-quarter inch of contact travel in oil. It may be noted that approximately one-third of the mass of the spring itself must be included as mass to be accelerated when designing these springs. As in the case of the d-c. breaker, this is a problem of high acceleration rather than high speed of travel since interest in the speed of opening is confined largely to the first one-quarter inch of travel, that is, the amount of travel necessary to part the contacts and produce an arc. Through the action of the blowout magnet, this arc will be transferred to arcing horns and lengthen rapidly independent of the speed of contact travel. Of course, one terminal of each arc must be maintained on the moving contact, but tests have demonstrated that with the moving contact shaped to provide a horn, the arc terminal will travel on this horn ahead of the contact under the action of a blowout field.

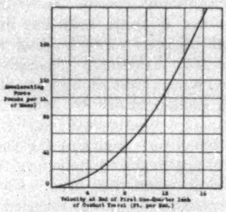

FIG. 8—RELATION OF ACCELERATING FORCE TO CONTACT VELOCITY. (IN OIL)

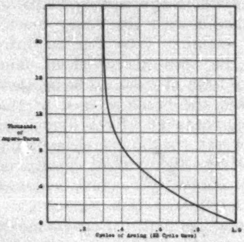

FIG. 9—VARIATION IN DURATION OF ARCING WITH HIGH-SPEED A-C. CIRCUIT BREAKER FOR VARYING VALUES OF MAGNETIC BLOWOUT FIELD

Fig. 9 shows the effect of a blowout field on the duration of arcing in a high-speed oil circuit breaker. The effect is quite marked for the lower values of field strength but the curve finally becomes asymptotic as the field is increased in strength and a point is eventually reached at which no further reduction is obtained in the period of arcing by increasing the excitation of the blowout magnet. This point, however, is well within a half-cycle of arcing on a 25-cycle wave and meets the requirements of present-day a-c. railway service.

The design of the blowout magnet will vary somewhat depending on the service in which the breaker may be applied. Where only low values of short-circuit current are to form a large proportion of the interrupting duty, a full iron return circuit may be used to work well below the saturation point. If heavy short circuits are anticipated, better results will be obtained with a magnet having a small section of return circuit designed to saturate at six to eight thousand amperes and forcing an air return path for the high current values. This is in order to eliminate the possibility of lengthening the arc unduly fast for very high current values having a heavy blowout force inherent in themselves. Care must also be taken in the design of this magnet from the point of view of temperature rise, bearing in mind that it must be excited by a series a-c. coil, and adequate means provided for radiation of heat. In this connection it may be noted that this application in railway service imposes a duty on trolley feeder breakers somewhat more severe than the standard N. E. M. A. duty cycle in that they may be called upon to perform more than the stipulated two OCO operations at full rated current, or a proportionately greater number at lesser current values, before an opportunity is afforded of renewing the oil. Provision should then be made in the design for a substantially larger amount of oil in the interrupting chamber than is required for conventional breakers of the same interrupting rating, and this increased body of oil will be of material benefit in taking care of heat radiation.

The design of mechanical latch for retaining the contacts in the closed position must receive careful attention in order to insure that the time of unlatching is reduced to a minimum. The conventional form of circuit breaker latch with right-angled holding face involves inherent time delay in that the holding face must be moved well over the center of the roller before opening motion can start. With the heavy accelerating spring used, this form may also result in heavier latch loads than are desirable for high-speed tripping.

Fig. 10 shows the details of a high-speed latch mounted in a common frame with the tripping magnet, forming an integral unit. The roller element of this latch is mounted on a floating lever linked to the contact lift rod and accelerated with it on opening. The primary latch presents an inclined surface to this roller in such manner as to give an angle of thrust well inclined toward the open position so that the movement of the floating lever and roller in opening starts simultaneously with the movement of the latch in releasing. This primary latch is maintained in the closed position by a secondary latch requiring only about one-eighth of an inch movement to release. In operation, the tripping magnet raises the secondary latch, allowing the primary latch to release under the impulse of its own latch load and at the same time permitting the floating lever and contact to start toward the open position. The floating lever is retrieved to the latched position with the contacts open and revolved about the latch roller as a fulcrum to the closed contact position by the closing mechanism. An over-center toggle in the operating linkage maintains the breaker in the closed position until it is again tripped. Thus, by utilizing different centers in the floating lever as a fulcrum at different stages of the movement, trip-free action is obtained at any point in the closing stroke.

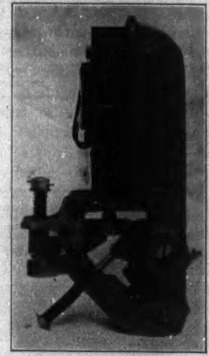

Fig. 10—Shunt Tripping Magnet and Latch for High-Speed A-c. Circuit Breaker

A d-c. shunt tripping magnet designed for use with the high-speed oil breaker is shown in Fig. 10. This magnet while necessarily enclosed within the breaker chamber, should be so located as to be freely accessible upon the removal of a cover in the main breaker casting. Fig. 7 shows a view of the breaker with the cover removed, exposing the magnet. This magnet is of the conventional laminated form, rather liberal in design so far as the magnet itself is concerned, but with the mass of the armature reduced to a minimum since it must be picked up very quickly. With the design of latch used here, the air-gap may be reduced to about five-sixteenths of an inch with a working travel of from one-eighth to three-sixteenths. To obtain the most suitable magnet, a low resistance coil will be necessary but external resistance may be used in the circuit where it is desired to maintain tripping current within the limits of battery supply for simultaneous tripping of a number of breakers.

Fig. 11 shows a view of the mechanism housing of a high-speed a-c. breaker with the covers removed. A closing solenoid, designed for 125-volt d-c. control, is mounted as an integral part of the breaker unit together with the necessary control panel, rotary type auxiliary switches, and a heater unit to prevent condensation inside of the housing under certain atmospheric conditions. As in the case of the d-c. high-speed breaker, such auxiliary switches as operate in unison with the main breaker contacts are moved to one position by a linkage operated by the closing of those contacts but on the opening of the breaker contacts, are retrieved to the opposite position by a spring. This is to reduce the load on the main accelerating spring when opening as well as to relieve the switches of the mechanical stresses incident to high-speed operation.

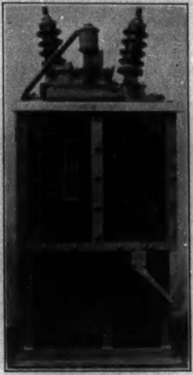

Fig. 11—Rear View of High-Speed Circuit Breaker for A-c. Railway Service Showing Control Mechanism

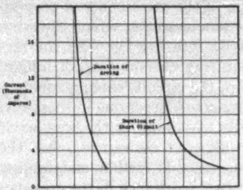

Fig. 12—Time Characteristics of High-Speed A-c. Circuit Breaker on Short-Circuit Test.
Including Time of Relay and Shunt Trip

Fig. 12 shows the time characteristics of a high-speed a-c. circuit breaker on short-circuit test, including the operating time of the high-speed relay and shunt trip. This breaker is designed to interrupt short-circuit currents of from 2000 amperes upward in 0.04 sec. (one cycle on a 25-cycle wave) after the occurrence of a fault. For current values of from 15,000 amperes upward, the breaker operates rather consistently in one-half cycle when the short circuit originates at or shortly after the zero point of the wave. In the event of the fault occurring relatively late in any given half-cycle, it will often persist through the next half-cycle before interruption. For current values of less than 2000 amperes, the time of interruption will still be of the order of one cycle but due to the inherently low blowout values involved as well as the necessity of varied relay settings to secure selectivity, the short circuit may persist for an additional half-cycle. Tests made at current values of from 10,000 to 15,000 amperes over a voltage range of from 1500 to 12,000 volts show no appreciable difference in the duration of arcing, indicating that within the range of service voltage in present-day railway applications, the time of circuit interruption for a breaker of this type is independent of initial circuit voltage. Fig. 13 is an oscillographic record of performance on short-circuit test at 11,000 volts.

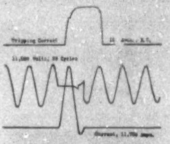

Fig. 13—Oscillogram Showing Performance of High-Speed A-c. Circuit Breaker on OCO Duty Cycle

A word as to the problems confronting the design engineer in attempting to apply high-speed breaker operation of this type to higher a-c. voltage service or to multiple-phase circuits. It has been pointed out in this paper that an auxiliary blowout field is essential to high speed interruption at the lower current values. Obviously, to be efficient the blowout field must be so distributed as to supply not only an intense field at the point of origin of the arc but also a properly graduated field over the whole area in which the arc may exist at any stage of its interruption. As the service voltage increases, requiring the drawing of longer and longer arcs to rupture the circuit, these magnets must control ever increasing areas, becoming in themselves more and more unwieldy to support in the breaker chamber with adequate insulation clearances. As the magnetic structure thus extends farther and farther downward into the clear break distance in the open position of the contacts in the effort to control the arcing area, the travel of the contacts must be increased by a safe amount to secure the necessary break distance for preventing reestablishment, thus increasing the over-all height of the breaker structure and, incidentally, its cost. As we approach the point in service voltage at which static shielding becomes necessary, these problems become so serious as to suggest seeking some method of securing the desired circuit conditions other than by the use of high-speed breakers.

As to application in multiple-phase circuits, it is obviously unsafe to permit the contacts of any single pole of a multiple-pole breaker to be operated independently of the other poles. This means that the tripping point must be so located as to control all of the linkage inside of all pole units as well as such linkage outside of these units as may be necessary to operate the several poles from a central point. This involves at once an increase of many times the mass to be accelerated at high speed and calls for a class of mechanical design not hitherto used to any extent in switching apparatus. At the best, there must be a very material increase in the power of accelerating springs used, and this power must again be reflected in increased closing loads creating an additional problem not only of design but of application as well.

In general the conclusion may be drawn that from the design point of view, adequate high-speed circuit breakers can be supplied to meet the present-day requirements for machine protection in d-c. railway circuits as well as such requirements as may be foreseen for some time to come. Also, adequate high-speed circuit breakers can be supplied to meet the requirements for protection for 25-cycle, single-phase, railway electrification work up to 12,000 volts. High-speed a-c. breakers for the next one or two steps above this in operating voltage for single-phase railway service seem within easy reach although not developed at the present time due to an absence of demand for breakers at these voltages. A-c. breakers of this type for high-tension circuits, or for multiple-phase circuits at any voltage are not at the present time available, and seem to present problems requiring a substantial amount of development work before they may become available.

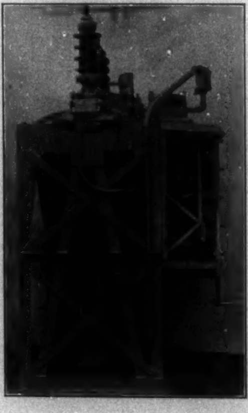

Fig. 14—Side Elevation of 15-Kv., High-Speed Circuit Breakers for A-c. Railway Service

## Discussion

For discussion of this paper see page 1311.

# Operating Experience with High-Speed Oil Circuit Breakers

BY B. F. BARDO[1]
Non-member

***Synopsis.**—This paper outlines the experience of the New York, New Haven and Hartford Railroad with three high-speed oil circuit breakers which were installed in 1925 to serve an electrified branch line carrying freight and passenger traffic, both local and through.*

*Satisfactory operation of paralleling commercial communication circuits, as well as of its own, presented an immediate problem, which after study outlined in the paper, finally yielded, and the answer, in part, was high-speed circuit breakers. The electrical and mechanical characteristics of these are set forth in detail and illustrated.*

*A number of tests of the circuit breakers and communication circuits made by short-circuiting the 11,000-volt lines on the branch showed currents up to 3000 amperes, and openings in from one-half to one and one-half cycles, with satisfactory operation of commercial and railroad communication plant.*

*A detailed record of the service operations of the circuit breakers along with a statement of failures is given. It is proper to say that the latter were more numerous in the early days of their use than they have been in recent months, and that a number of the faults are chargeable to the railroad's urgent need for the equipment, thereby considerably limiting the development and testing time desired by the manufacturer.*

*While it was not discussed in detail in the paper it goes without saying that in the design and installation of the circuit breakers safety was a paramount consideration. The illustrations will provide an index of this in the general arrangement of equipment, and also in the screen placed horizontally around the structure at the floor level to prevent curious small boys from climbing in to investigate.*

### CHARACTER OF SERVICE AND ELECTRIFICATION

BEFORE discussing in detail the New Haven Railroad's experience with high-speed oil circuit breakers, it will be of interest to review briefly the reasons for their installation.

In the latter part of 1924, decision was made to electrify the Danbury Branch, comprising 23.82 mi. of main, along with 5.1 mi. of passing or side track between South Norwalk, Conn., in the New Haven's electric zone, and Danbury, Conn. The service at that time consisted of an average of six passenger trains, two through freight trains, one milk train, and one local freight train per day in each direction. The system of electrification was to be essentially the same as that in use on the main line, between New York and New Haven, Conn., namely, 11,000 volts, single-phase, 25 cycles, using an overhead contact wire and track rail return. A schematic diagram of the distribution system, as finally adopted, is shown in Fig. 1.

### COMMUNICATION FACILITIES

On the branch to be electrified the New Haven had open wire communication circuits used by the Western Union Telegraph Company and itself respectively. Furthermore, on private property immediately adjoining and paralleling the company's right-of-way for nearly half of the distance and on public highway for the balance of the distance was a commercial open wire telephone line, this being more or less spread out in the various towns along the way. Therefore, an immediately important problem was to decide how best to provide for satisfactory operation of paralleling commercial and its own communication circuits, and at the same time not make the electrification itself too involved, from an operating standpoint, or too expensive from a maintenance standpoint.

### STUDIES MADE

Various schemes were studied involving the use of reactors in the trolley and feeder circuits at South Norwalk (see Fig. 1), along with booster transformers, balancing transformers, and supplementary return circuit, independent of the running rails, the induced voltages and other effects in each case being based upon the average duration of short circuit as determined by oil circuit breakers standard elsewhere in the electrified zone. The results of these studies indicated that the electrification and the communication circuits could be so designed that they would operate satisfactorily, using existing standard circuit breakers to interrupt short circuits, but this involved the installation of a number of series booster transformers, which were not desirable from railroad operating point of view.

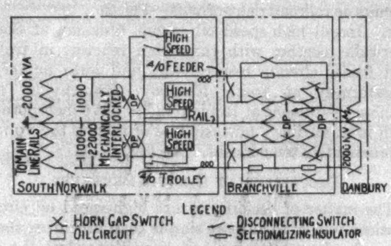

FIG. 1—NEW YORK, NEW HAVEN & HARTFORD RAILROAD COMPANY, DANBURY BRANCH

Schematic diagram of electric power distribution

At this point the installation of high-speed oil circuit breakers at South Norwalk was proposed, with the understanding that while they would not decrease the magnitude of the voltage induced in the communication circuits, yet by virtue of their quick operation, they would materially reduce interference in both railroad and commercial communication circuits. It was decided that circuit breakers of this kind would be more desirable than booster transformers, and therefore the following program, satisfactory to all interests, was adopted:

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[1] Supt. of Elec. Transmission, N. Y., N. H. & H. R. R. Co., New Haven, Conn.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

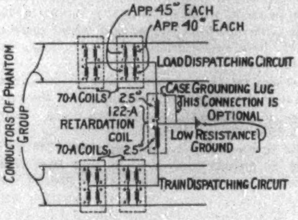


Fig. 2—Danbury Branch—Communication Circuit Drainage

a. Place paralleling commercial communication circuits in cable on the public highway.

b. Install adequate drainage on communication circuits on railroad right-of-way—Fig. 2.

c. Install high-speed oil circuit breakers at South Norwalk together with three-ohm reactor, in trolley and feeder circuits respectively, and auto balancing transformers at South Norwalk, Branchville, and Danbury,—the one at Branchville to have incorporated with it an auxiliary unit capable of raising the voltage approximately ten per cent. See Fig. 1.

## Description of Circuit Breakers

The matter of deciding to use high-speed oil circuit breakers proved to be more simple than procuring them. Some development work had been done, but the circuit breaker was not then in commercial production, and considerable pressure was required to convince the manufacturer that three should be built. This, however, was finally arranged, and they were built early in 1925.

Each of these carries a normal rating of 800 amperes at 16,500 volts, 25 cycles. The maximum interrupting capacity approximates 35,000 amperes. Direct current is used for control normally at 250, but with a standby supply at 500 volts. The tripping operation is started by solenoids, of which there are two, connected in parallel on the lower, and in series on the higher voltage. The actual tripping work is done by spiral springs, these being compressed during the closing operation by a 110-volt, 25-cycle, single-phase motor operating through a train of gears. The circuit-breaking mechanism is in the shape of an inverted letter "T," with a blowout coil, in series with the circuit to be broken, on each stationary contact. The entire assembly is immersed in insulating oil, and enclosed in a substantial sheet steel cylindrical tank, suitably vented. Two condenser type bushings, each terminating in a removable stationary contact within the tank carry the current, and the whole is supported by four angle steel legs to which are bolted cast iron feet. There is an individual current transformer of the outdoor type for each circuit breaker, which is directly connected to an overload coil, also for each circuit breaker. Irrespective of the location of the short circuit, whether on trolley or feeder, it is desirable to open both trolley and feeder circuit breaker, and this is accomplished by auxiliary contacts on each overload relay so connected that when one circuit breaker opens the other will immediately follow, thus clearing the line.

## Installation

Three circuit breakers were installed on a steel platform 27 ft. by 10 ft., with reinforced concrete house directly underneath, and change-over horn-gap switches directly overhead. Reference to Fig. 1 will show that any of the three circuit breakers may be used in any combination, two at a time. Fig. 3 shows an elevation of circuit breakers as installed, and Fig. 4 of the entire substation of which they are a part.

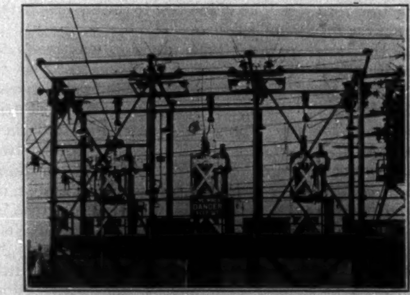


Fig. 3—High-Speed Circuit Breakers, South Norwalk

## Communication Line Protection

The method of applying drainage to communication circuits is as follows: The physical circuits are drained by two No. 70-A repeating coils so connected that both primary and secondary windings are in multiple. The midpoints of these windings are then connected to ground through one winding of a No. 122A coil, which acts also as a drain on the phantom circuit. A combination such as this was installed at each end of the branch and at six intermediate points approximately uniformly spaced from each other.

## TESTS

In the early part of October 1925 a series of tests was made jointly by the American Telephone and Telegraph Company and the New Haven to determine the extent to which the high-speed circuit breakers, as well as the communication line drainage, etc., contributed to satisfactory operation. Oscillograph records of these tests were made, three of which are reproduced here. They are:

FIG. 4—SUBSTATION AT SOUTH NORWALK

Fig. 5—A short circuit at Danbury, 23.8 mi. from the oscillograph, the latter being at point of supply, South Norwalk. The circuit was opened in one cycle (1/25 sec.) and the current reached a maximum of 1000 amperes.

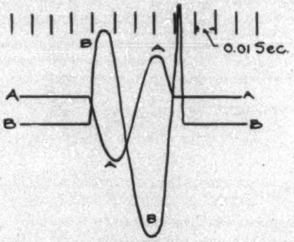


FIG. 5—SHORT CIRCUIT AT DANBURY—23.8 MI.

A. Trolley current—maximum 1000 amperes
B. Volts across drainage at South Norwalk—maximum 48.7 amperes

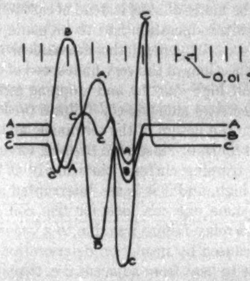
Fig. 6—A short circuit at Wilton, 7.4 mi. from South Norwalk, showing an opening in one and one-half cycles at a maximum 540 amperes.

Fig. 7—A short circuit at South Norwalk, one-half mile from the oscillograph, showing the circuit open in one-half cycle, the maximum current being 3030 amperes.

## CIRCUIT BREAKER OPERATION

Considering the three circuit breakers as a group, it may be noted that since being put in service in July 1925 the operation has been as follows:

| | |
|---|---|
| Total number of operations on grounds | 717 |
| Ave. number of operations on grounds per circuit breaker | 239 |
| Total number of other operations to 1-1-28 | 750 |
| Ave. number of other operations per circuit breaker | 250 |



Note - Behavior of B & C probably transient effect of Trolley & Feeder Circuit Breaker Openings

FIG. 6—SHORT CIRCUIT AT WILTON—7.4 MI.

A. Feeder current—maximum 560 amperes
B. Track current—maximum 685 amperes
C. Induced voltage—maximum 1420 amperes

The circuit breakers have not operated faultlessly and therefore the third, or so-called spare circuit breaker, has been of real use, but this was to be expected. There has been on the circuit breakers as a group, since their installation, a total of 25 operating failures distributed as follows:

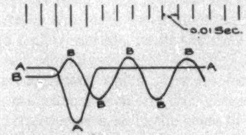


FIG. 7—SHORT CIRCUIT AT NORWALK—0.5 MI.

A. Trolley current—maximum 3030 amperes
B. Induced voltage, S. N. E. Tel. Co.—maximum 180 amperes.

| | |
|---|---|
| Trip coils | 5 |
| Mechanical parts | 5 |
| Closing motor | 2 |
| Overload relay | 1 |
| Indicating switch | 2 |
| High-tension terminal | 1 |
| Unknown | 9 |
| Total | 25 |

Of the above failures those due to mechanical causes have been most difficult to find. Adjustment in length of operating rod had to take into consideration proper sequence of events as between main and auxiliary contacts, along with irregularities on the main contacts due to arcing. If this operating rod length was not correct within fairly close limits the circuit breaker would not close and latch, although it would open satisfactorily. The forged steel spiral-spring ends in the opening mechanism received severe punishment and had to be made heavier. Likewise the foot castings on the legs had to be made of steel instead of cast iron, and the indicating switch operation had to be made somewhat more positive. In general the mechanical difficulties have been reflections of the very high speed of operation, with resultant high starting and stopping stresses.

On the electrical side trip coil failures predominated, due partly to the design of the terminals, and partly to the fact that for some reason the tripping circuit did not open. The tripping current, particularly at 250 volts, is relatively high, and if it is not interrupted as soon as its work is done one can look for trip coil difficulty. The overload relay failure was due to a ground on one of its leads caused by insulation deterioration which in turn was due to heat from adjacent d-c. tripping circuit arc. Barriers have eliminated the possibility of further difficulties due to this source. The motor failures were such as are sometimes found in motors of this nature and involved adjustment of short-circuiting device and cleaning of commutator.

In general, the statement is justified that most of the faults uncovered by our operation would not have appeared if the manufacturer had been given more time to develop the design and test it completely before installation.

### OPERATION OF COMMUNICATION CIRCUITS

It may be of interest to note that the program outlined in paragraph three, parts a, b, and c, has resulted in satisfactory operation to commercial as well as railroad communication circuits.

### ACKNOWLEDGMENT

The writer desires to acknowledge kind assistance of Messrs. H. A. Shepard, general superintendent of electric transmission and communication department, S. Withington, electrical engineer, as well as his assistant, H. Brown, and A. R. Belmont, communication engineer.

## Discussion

For discussion of this paper see page 1311.

# Arrangements of Feeders and Equipment for Electrified Railways

BY R. B. MORTON[1]

Fellow, A. I. E. E.

***Synopsis.**—This paper outlines the general requirements governing arrangements of distribution system and substation equipment for electrified railways. By way of illustration it presents a general description of the conversion and distribution facilities as recently installed in the electrification of the New York Connecting-Long Island Railroad to Bay Ridge, and in the electrification, now nearing completion, of the Philadelphia-Wilmington and West Chester lines of the Pennsylvania Railroad.*

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## INTRODUCTION

SUBSTATION equipment necessarily includes conversion apparatus required to translate the power received over transmission lines into suitable form for delivery to the contact system. Such apparatus is usually provided in units so proportioned as to load capacity that the outage of any one unit will not place limitations to the movement of traffic.

Switching equipment must be provided which, in the event of short circuits, will quickly and automatically interrupt the supply of power, and so confine the effect of such interruption as to cause the least practicable disturbance to movement of traffic. Although in practise it is necessary to include switching apparatus of more or less complexity, the ideal switching equipment would be none at all. It is obviously desirable to keep the switching equipment as simple as the nature of traffic requirements will permit.

The several examples of railway electrification, to which reference is made in this paper, are of a type utilizing the single-phase a-c. system of traction, but some of the features of switching arrangements herein described may also be applied in a d-c. system. Essentially in a d-c. system of traction there must be interposed between the step-down transformers and the trolley bus, suitable rectifying apparatus, such as mercury vapor rectifiers, motor-generators, or rotary converters.

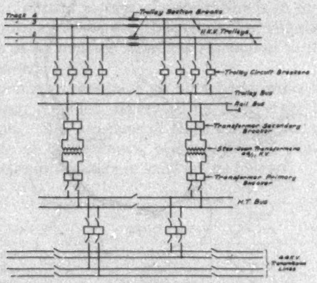
Track 4
3
2
1
Trolley Section Breaks
11 K.V. Trolleys
Trolley Circuit Breakers
Trolley Bus
Rail Bus
Transformer Secondary Breaker
Step-down Transformers 44/11 K.V.
Transformer Primary Breaker
H.T. Bus
44 K.V. Transmission Lines

FIG. 1—SCHEMATIC DIAGRAM OF TYPICAL SUBSTATION

Pennsylvania Railroad—Paoli-Chestnut Hill Electrification

There may be said to be at least four rather distinct methods of arranging the switching equipment in substations, namely:

1. An arrangement which provides for switching, under load, the transmission circuits, high and low sides of transformers and trolley feeders, as in the case of the original Paoli-Chestnut Hill electrification of the Pennsylvania Railroad (Fig. 1).

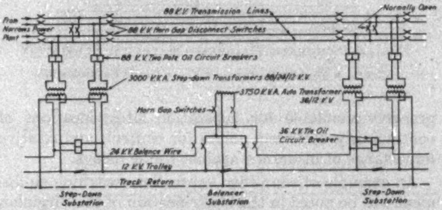
From Narrows Power Plant
88 K.V. Transmission Lines
Normally Open
88 K.V. Horn Gap Disconnect Switches
88 K.V. Two Pole Oil Circuit Breakers
3000 K.V.A. Step-down Transformers 88/24/12 K.V.
3750 K.V.A. Auto Transformer 36/12 K.V.
Horn Gap Switches
36 K.V. Tie Oil Circuit Breaker
24 K.V. Balance Wire
12 K.V. Trolley
Track Return
Step-Down Substation
Balancer Substation
Step-Down Substation

FIG. 2—DIAGRAM OF TYPICAL STEP-DOWN AND BALANCER SUBSTATIONS

Virginian Railway Electrification

2. An arrangement which provides for switching on the high tension side only for controlling both transmission and trolley circuits, as in the case of the Virginian Railway (Fig. 2).

3. An arrangement which provides for switching, under load, the transmission and trolley feeder circuits, but not the transformers, as in the cases of the original electrification of the Elkhorn Grade on the Norfolk & Western Railway (Fig. 3) and the New York Connecting-Long Island Railroads (Fig. 5).

4. An arrangement which provides for switching under load, on the low tension side only, for controlling both high-tension and low-tension circuits, the transformers being switched and regarded as a part of the transmission system, as in the case of the recent Pennsylvania Railroad Suburban and Through Electrification (Fig. 7).

In the selection of a scheme of distribution for a rail-

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[1] Project Engineer, Gibbs & Hill, New York, N. Y.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

way electrification, the principal governing factors, not necessarily in the order of their importance, may be listed as follows: source of power; type of system used on any existing electrification to which the new electrification may be joined; maximum concentration of power required for movement of traffic; distances involved, and probabilities of future extension; number of tracks; alinement of railroad and topography of route; property available for substation sites; locations of continuously attended points for control; and relative importance of insurance against traffic delays.

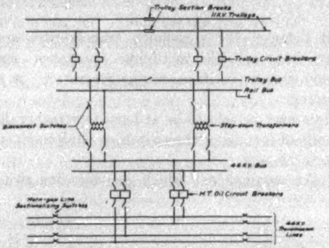
Trolley Section Breaks
11 K.V. Trolleys
Trolley Circuit Breakers
Trolley Bus
Rail Bus
Disconnect Switches
Step-down Transformers
44 K.V. Bus
H.T. Oil Circuit Breakers
Horn-gap Line Sectionalizing Switches
44 K.V. Transmission Lines

FIG. 3—SCHEMATIC DIAGRAM—MAYBEURY SUBSTATION

Norfolk & Western Railway—Elkhorn Grade Electrification

An example of simplified substation switching equipment will be noted in the electrification of the Virginian Railway. This system has been described in detail in a paper[2] recently presented before the American Society of Civil Engineers. In a typical substation serving the single track portion of this railroad there are provided three oil circuit breakers. Two of these are high-tension breakers, interposed between the transmission lines and the step-down transformers, while the third is a low-tension breaker, serving to equalize the load on the transformer secondaries, or, in the event of one of the transformers or one of the transmission lines being out of service, serving to feed both trolley sections from one transformer. Fig. 2 shows in diagram the arrangement of power connections.

The balancing wire system of distribution for the Virginian Railway electrification was adopted mainly for the following reasons:

With main substations spaced on an average about 20 mi. apart, it was possible, because of the circuitous alinement of the railway, to shorten materially the over-all length of the transmission line. The saving in cost resulting from this factor, combined with the savings due to simplified switching arrangements in substations, partly offset the higher cost of transformers and the cost of the 24-kv. balancing wire. The advantage of a system which materially reduces the effect of inductive disturbances on paralleling communication wires was therefore secured, but, however, at some expense.

In a railway electrification comprising two or more main running tracks, the contact system is usually sectionalized in such a manner that a power outage on one track will not interfere with traffic movements on the remaining tracks. This necessitates a trolley circuit breaker for each trolley section.

The electrification of the New York Connecting Railroad–Long Island Railroad to Bay Ridge, completed and placed in operation during the summer of 1927, may be taken as illustrative in the arrangement of its feeders and substation equipment. A general description of these features may be of interest.

### NEW YORK CONNECTING RAILROAD–LONG ISLAND RAILROAD TO BAY RIDGE

This electrification covers a route 20 mi. in length, extending from a freight terminal yard at Bay Ridge, Brooklyn, to a point of connection with the Harlem River Division of the New York, New Haven & Hartford Railroad at Port Morris, Borough of the Bronx (Fig. 4).

Freight traffic only is handled, with the exception of a few passenger trains daily over the Hell Gate Bridge route, which service was inaugurated in 1917. Freight movements consist of through freight trains operated by the New Haven Railroad between Bay Ridge and Port Morris, way freight and through freights operated by the Long Island Railroad between Bay Ridge and Fresh Pond Junction, and yard switching at Bay Ridge and New Lots.

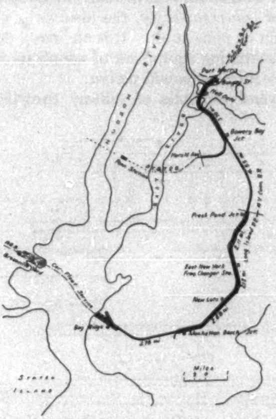
Hudson River
East River
Port Morris
Hell Gate
Bowery Bay Jct.
Harold Ave.
Penn. Station
Penn. R.R.
Fresh Pond Jct.
Long Island R.R.
East New York Freq. Changer Sta.
New Lots
Bay Ridge
Manhattan Beach Jct.
Car Float Service
Greenville Yard
Staten Island
Miles

FIG. 4—MAP OF ELECTRIFIED SYSTEM

New York Connecting Railroad—Long Island Railroad—Bay Ridge Improvement

*Power Supply.* The system of electrification is fundamentally an extension of the New Haven electrification, with 11,000-volt trolleys and 11,000-volt feeders of opposite polarity, forming a 22,000-volt, three-wire system. At present, power for operation is received from the New Haven system, which in turn is supplied principally from its own generating station at Cos Cob, approximately 42 mi. from Bay Ridge, and also in part from purchased power delivered to the New Haven at West Farms, Devon, and New Haven.

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[2] New York, February 1, 1928, by Mr. George Gibbs.

A variable-ratio frequency changer of 5000 kw. continuous rating at 70 per cent power factor has been provided at East New York, in an addition to one of the substations of the Long Island Railroad. This machine is capable of furnishing the single-phase railway system an emergency supply of power from the 11,000-volt, three-phase, 25 cycle bus, converting the same to power at 11,000 volts, single-phase, 25 cycles, and is also capable of acting as a flexible tie between the two power systems with ability to transfer a desired amount of power in either direction, independently of frequency variations up to a total spread of 6 per cent, equivalent to 1½ cycles. This set is also operated during peak load periods as a synchronous condenser for power-factor correction on the single-phase railway system, for the purpose of improving trolley voltage. When so operated, with the three-phase end of the set electrically disconnected, an automatic voltage regulator so controls excitation as to maintain practically uniform voltage up to a point where the single-phase machine is carrying full rated load of 7000 kv-a. If the system conditions require a loading in excess of 7000 kv-a. to maintain normal voltage, the excitation is so controlled as to automatically droop the voltage, keeping the stator current at an average value corresponding to full load in amperes.

*Substations.* A total of six auto-transformer stations have been provided, separated by an average interval of 3.8 mi. The locations of these substations, number and size of transformers, and number of trolley and feeder circuit breakers in each are as follows:

| Location | Auto-transformers | Trolley breakers | Feeder breakers |
|---|---|---|---|
| Bungay Street | 1—3000 kv-a. | 5 | 6 |
| Bowery Bay | 1—3000 kv-a. | 9 | 6 |
| Fresh Pond | 1—3000 kv-a. | 9 | 6 |
| New Lots ("NO") | 1—3000 kv-a. | 9 | 6 |
| Manhattan Beach Jct. | 1—3000 kv-a. | 7 | 8 |
| Fourth Ave., Bay Ridge | 2—3000 kv-a. | 6 | 4 |

The transformers are of the outdoor type, self-cooling, and have a turn ratio of 22,000:11,000 volts. The rating as an auto-transformer corresponds to a coil rating of 1500 kv-a. for each half of its winding. The transformers are capable of carrying 150 per cent of rated load for one hour, following continuous rated load, and this followed by 300 per cent of rated load for five minutes.

The transformers are connected to trolley and feeder buses through two-pole, 22,000-volt motor operated horn-gap switches, capable of safely rupturing transformer exciting current.

A schematic diagram of one of the substations, indicating the arrangement of connections of trolleys and feeders is shown in Fig. 5. It will be noted that at this substation, two of the four feeders are tapped and the other two are looped. At the next adjacent substations the order is reversed.

Trolley and feeder oil circuit breakers are of compact design, similar to breakers which are used on the New Haven system. They have a current rupturing capacity of about 3000 amperes at 11,000 volts. Short-circuit currents for trolley or feeder short-circuits adjacent to a substation may reach maximum values considerably in excess of this value. In order to avoid imposing on the circuit breakers of the Bay Ridge system, or on the similar breakers of the New Haven system, a current rupturing duty beyond the interrupting capacity of those breakers, an arrangement of oil circuit breakers is provided on the New Haven system at its Cos Cob power plant and at each other point where purchased power is received, whereby a flow of current of the magnitude of a short circuit causes resistances to be momentarily cut into the trolley and feeder circuits at such supply points. This reduces the flow of short-circuit current to a nominal value. The Bay Ridge breakers have been given a predetermined time delay of one second following the occurrence of a short-circuit, before the tripping circuit is completed, which insures that these breakers shall be required to rupture but a comparatively small current. After slightly more than one second, the several resistances are automatically cut-out and normal voltage is restored to the system.

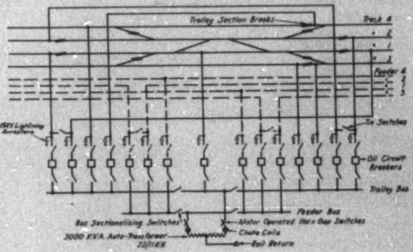

Fig. 5—Schematic Diagram—"NO" Substation

New York Connecting Railroad—Long Island Railroad—Bay Ridge Improvement

All auto-transformer substations are unattended. The circuit breakers and motor operated horn-gap switches in each substation are controlled from a panel mounted in a signal interlocking tower nearest to that station. In the case of Bowery Bay substation it was necessary to utilize a system of supervisory control from Bungay Street tower, a distance of three and a half miles.

*Distribution System.* The feeder side of the three-wire distribution system comprises four 4/0 copper conductors extending the entire length of the line, as far as Bay Ridge substation. These feeders are carried on pin type insulators of 45,000 volts service rating. Between Fresh Pond and East New York is a four-arch tunnel, 3500 ft. long, in the outside walls of which are banks of cable ducts. Through these ducts four paper insulated, lead sheathed cables of 350,000 cm. are used.

The trolley system for all main running tracks comprises a 4/0 bronze contact wire, 65 per cent conductivity, reinforced by a 4/0 copper auxiliary, supported by a 19-strand messenger ⅝ in. diameter, of high strength bronze. In yard construction the copper auxiliary is omitted.

*Track Return.* All rail joints on main tracks are single bonded with a No. 1 bond, gas welded to the head of the rail. In yard tracks one rail only is bonded. Cross bonds are installed at intervals along the main line to cross-connect the mid-points of impedance bonds.

The three-wire system of distribution was selected for the New York Connecting Railroad–Long Island Railroad, Bay Ridge line, mainly for the reason that this electrification is fundamentally an extension of the existing electrification of the New York, New Haven & Hartford Railroad. The distances from the sources of power are considerable, but are within the range of economical transmission for the voltage employed. Circuit breakers of relatively low current rupturing capacity are used because they are adequate for the conditions of power supply and because they afford a considerable saving in first cost as compared with breakers of larger current rupturing capacity.

## PHILADELPHIA SUBURBAN ELECTRIFICATION OF THE PENNSYLVANIA RAILROAD

The electrification of Maryland Division, main line, from Philadelphia to Wilmington, Del., a distance of about 27 mi., and of the Wawa Branch to West Chester, a distance of about 26 mi., is now nearing completion (Fig. 6). Approximately 105 mi. of electrified track are involved in the main line work, and approximately 50 mi. in the Branch.

Substations have initially been equipped for supplying power for the operation of multiple unit trains only, but the Wilmington line has been designed to later form a part of through electrification between New York and Washington, with locomotive operation of main line freight and passenger services.

*Power Supply.* Power for the electrification is supplied by the Philadelphia Electric Company at 13,200 volts, 25 cycles, single-phase, delivered on the bus bars of the Railroad Company's step-up station at Lamokin Street, Chester. Three self-cooled single-phase transformers of 15,000-kv-a. continuous rating are provided for stepping up this power to a transmission potential of 132,000 volts. This transmission potential was selected by reason of the large amounts of power which will be required for the ultimate through electrification, and the considerable distances to be covered.

Initially two transmission circuits of 4/0 copper are provided, which are supported on the catenary structures. Ultimately it is planned that the number of transmission circuits along the main line may be increased to four.

*Substations.* A total of nine substations are provided in which the power is stepped down to a trolley potential of about 11,000 volts. The locations of these stations, number and size of step-down transformers and the number of trolley circuit breakers in each are as follows:

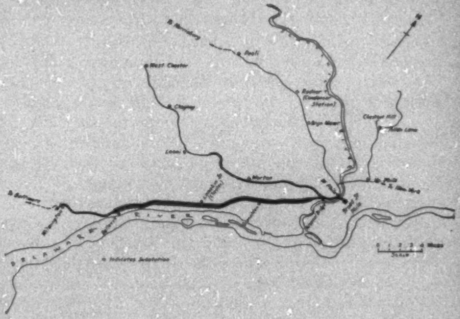

FIG. 6—MAP OF PHILADELPHIA SUBURBAN ELECTRIFICATION, PENNSYLVANIA RAILROAD

| Location | Transformers | Trolley breakers |
|---|---|---|
| Wilmington | 2—4500 kv-a. | 4 |
| Bellevue | 2—4500 kv-a. | 10 |
| Lamokin | 2—4500 kv-a. | 10 |
| Glenolden | 2—4500 kv-a. | 8 |
| Arsenal Bridge | 2—4500 kv-a. | 9 |
| Morton | 2—4500 kv-a. | 4 |
| Lenni | 2—4500 kv-a. | 3 |
| Cheyney | 1—4500 kv-a. | 1 |
| West Chester | 2—4500 kv-a. | 1 |

The average interval between substations is 6.4 mi.

It is planned that the number of step-down transformers in each of the substations serving the main line may ultimately be increased to four.

The transformers are self-cooling, and are capable of carrying continuous rated load, followed by 150 per cent of rated load for two hours, followed by 300 per cent of rated load for five minutes.

A schematic diagram of one of the substations, indicating the arrangement of connections, is shown on Fig. 7.

A feature of these substations, as well as of the step-up substation, is the absence of oil circuit breakers in the high tension side.

In the step-up substation oil circuit breakers are provided in the low tension side of the transformers, giving automatic protection in the event of transmission line fault. The transformers are connected on the high tension side to outgoing transmission lines through two-pole 132-kv. air sectionalizing switches, remote electrically controlled, which are not to be opened under load, but are capable of interrupting transformer exciting current.

In a similar manner the transformers in each of the step-down substations are connected to the high-tension lines through air sectionalizing switches, and the low tension side of each is connected to trolley and rail buses through a two-pole oil circuit breaker, arranged for automatic tripping on reverse power, on unbalanced voltage on the high tension side, or by differential protection against failure on the trolley bus or within the transformer. A fault on any part of a 132-kv. transmission circuit will trip out of service one transformer in the step-up station and one transformer in each step-down station which is served by the transmission line on which the fault occurs. Such an outage does not affect train operation, as sufficient transformer capacity remains in each substation to handle maximum expected loads. If the transmission line fault is to ground only, and does not involve the opposite conductor, the flow of current through the earth, back to the step-up station is limited to about 200 amperes by a neutral resistance connected to the mid-point of each step-up transformer.

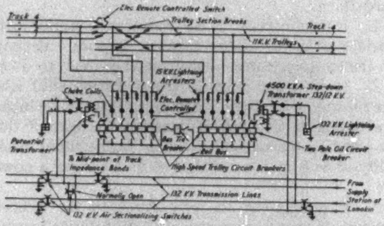
Elec. Remote Controlled Switch
Track 4
Trolley Section Breaks
Track 4
11 K.V. Trolleys
15 K.V. Lightning Arresters
Choke Coils
4500 K.V.A. Step-down Transformer 132/12 K.V.
Elec. Remote Controlled
132 K.V. Lightning Arrester
Potential Transformer
Bus Tie Breaker
Rail Bus
Two Pole Oil Circuit Breaker
To Mid-point of Track Impedance Bonds
High Speed Trolley Circuit Breakers
Normally Open
132 K.V. Transmission Lines
From Supply Station at Lamokin
132 K.V. Air Sectionalizing Switches

FIG. 7—SCHEMATIC DIAGRAM—BELLEVUE SUBSTATION

**Pennsylvania Railroad—Philadelphia Suburban Electrification**

Trolleys are sectionalized at each substation and each trolley section is normally fed from each end, thereby avoiding "stub-end feed." Trolley circuit breakers are designed to open under short circuit within an interval of time not exceeding 1/25 sec. The rupturing capacity of these circuit breakers is 50,000 amperes. This high value of rupturing capacity was required with a view to ultimate conditions as to transformer capacity at step-up and step-down substations. This installation represents the first use on any extensive scale of quick opening circuit breakers in a-c. railway electrification, and it is expected that inductive disturbances and damage to overhead wires and insulators resulting from trolley short circuits will be minimized by the quick acting feature.

At each substation there is provided a small building to house a control storage battery and charging equipment, protective relays and oil conditioning apparatus. All other equipment is of outdoor type.

Substations are unattended, and are controlled from a panel containing control switches and indicating lamps placed in signal interlocking towers or other points continuously attended. Certain substations on the West Chester branch are so remote from a continuously attended tower that it was necessary to provide supervisory control for these substations, utilizing wire circuits in an aerial communication cable along the right-of-way.

*Contact System.* The contact system for all main running tracks comprises a 4/0 bronze contact wire, 40 per cent conductivity referred to copper, reinforced by a 4/0 copper auxiliary, supported by a 19-strand bronze messenger ⅝ in. diameter, of high strength and relatively low conductivity. No paralleling feeders were required. In yard construction the copper auxiliary is omitted.

*Track Return.* All rail joints on main track are double bonded, not for conductivity but to minimize signal failure due to broken bonds. A major portion of the trackage is bonded with No. 1 bonds, gas welded to the head of the rail, and on the remainder of the work No. 1/0 bonds with expanded pin terminals are used, installed where possible under the joint plates. Cross bonds of two No. 2/0 copper are installed at intervals to cross-connect the mid-points of impedance bonds.

The type of system of transmission, conversion, and distribution adopted for the Philadelphia-Wilmington electrification gives a high degree of selectivity in the automatic tripping of circuit breakers in the event of short circuits, and is adaptable to future extensions over considerable distances and to such increase in installed capacity as will be required for the future operation of through freight and passenger traffic. The West Chester line was equipped in a manner similar to the Philadelphia-Wilmington line, partly for the sake of uniformity of apparatus, and partly because the 132 kv. transmission lines will ultimately be used as a part of a transmission network, in connection with future extensions of the electrification on the main line to the West, and elsewhere.

## Discussion

For discussion of this paper see page 1311.

# Protection of Electric Locomotives and Cars
## to Operate with High-Speed Circuit Breakers

BY E. H. BROWN[1]
Non-member

***Synopsis.**—This paper discusses the requirements for protecting the high-tension circuits of an electric car or locomotive which operates on the a-c. single-phase system of electrification.*

*The means which must be employed to secure this protection is outlined. The types of relays used by the Pennsylvania Railroad for this purpose are described, together with the connected control circuits. These relays are known as pantograph lowering relays, and they make use of the opening of the substation breakers on a short circuit to disconnect the electrical equipment of the car or locomotive from the line by lowering the pantograph. Tests of high-speed relays recently developed indicate that these relays will give satisfactory service with high-speed circuit breakers in the trolley feeders at the substations.*

*In conclusion, results justify the elimination of circuit breakers from electric cars and locomotives by the substitution of the pantograph lowering relay.*

THE protection of the electrical equipment of an electric car or locomotive utilizing the a-c. single-phase system may be divided into two general problems:

1. Protection of the high-tension circuits and the transformer from damage due to grounds or short circuits.
2. The protection of the motors and their connecting low-tension circuits.

While the problems are associated, we will, for the purpose of this paper, consider only the problem involved in protecting the transformer and high-tension circuits from the results of short circuits, as transformer overload due to the operation of the motors will be taken care of by the operation of the overload devices in the motor circuits.

It was formerly the general practise, and this practise is still followed on many railroads using the single-phase system, to protect the transformer and the high-tension wiring by an oil circuit breaker of adequate capacity installed on the car or locomotive. On the Pennsylvania railroad, however, a somewhat different practise has been developed for the a-c. multiple unit car and locomotive equipment, as it has been found difficult to provide, in the space available on the cars or locomotives, an oil switch of a capacity adequate to open the high currents which are possible upon short circuit under our operating conditions. This practise is, in brief, to insert, between the pantograph and the transformer, a device known as a pantograph lowering relay, which makes use of the substation circuit breakers feeding the trolley wire instead of an oil circuit breaker on the locomotive or car. The method followed in the apparatus used is as given below:

In the circuit between the pantograph and the transformer is inserted a relay known as the pantograph lowering relay. When an excessive current passes through this circuit, the pantograph lowering relay initiates the operation of lowering the pantograph through the control circuits and electropneumatic operating devices. This operation cannot be completed until the opening of the substation breaker. The consequent removal of current from the pantograph and its connected circuit permits the relay to complete its operation which closes the control circuit to the pantograph lowering device and lowers the pantograph during the time that the substation breaker is out. It can readily be seen that this device must accomplish three things:

1. It must initiate the lowering operation prior to the opening of the substation breaker, because it depends on the excessive current flowing in the circuit to do so.
2. It must not complete this operation until after the substation breaker has opened, as it would be highly undesirable to attempt to interrupt the current flow by lowering the pantograph with the resultant possibility of severing the overhead contact wire by a power arc.
3. It must lower the pantograph in the interval between the time of opening of the substation breaker and the closing of this breaker by the substation operator.

Other features of the device are important and these will be dealt with in the following paragraphs:

It may readily be seen that after the device has functioned to lower the pantograph on a car or locomotive upon which the equipment is defective, the pantograph should not be raised by the ordinary means at the motorman's command. An interlocking must be provided at the pantograph lowering relay to prevent raising of the pantograph by the usual control methods.

It is also necessary that the pantograph lowering relay shall assure, as far as possible, that the pantograph on the car or locomotive, upon which the equipment is defective, shall remain lowered even though the latching device may fail and consequently means should be provided to retain the air in the lowering cylinders, thus preventing raising of the pantograph, even should the locking device fail.

The principal requirements will now be considered in detail, to point out the manner in which each affects the design of the relay. The first requirement, that the

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[1] Elec. Engg. Dept., Pennsylvania Railroad, Altoona, Pa.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

relay initiate the lowering operation before the substation breaker opens, is by far the most important. It is fundamental and upon the success of this first operation depends the whole sequence of the further events. When the use of the high-speed substation breaker was decided upon for the Philadelphia-to-Wilmington and the West Chester electrifications of the Pennsylvania Railroad, preliminary laboratory experiments demonstrated that the type of pantograph lowering relay which had previously been used would not operate with this type of breaker. While these relays had been satisfactory with the lower speed of operation of breakers in the existing substations, the high-speed breaker opening the short circuit as rapidly as one-half a normal cycle on 25-cycle current, would not permit a sufficient impulse to be received by the relay before power was off the line. It therefore became necessary to develop new relays requiring less energy input, but operating on the same current values as before. These newly developed types will shortly be described.

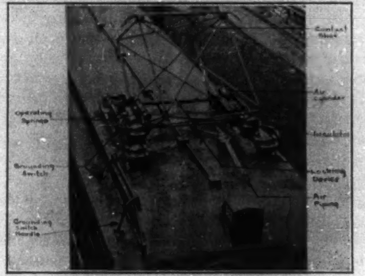

Fig. 1—Multiple Unit Car Pantograph

The second requirement for the relay is that it must not complete the operation of lowering the pantograph until the substation breaker is opened. This is an important function, but one which, with quick acting breakers especially, will seldom be called into effect. There is one condition, however, which makes this requirement most important. This condition exists when a short circuit occurs of sufficient value to trip the pantograph lowering relay, but does not operate the substation breaker immediately. The pantograph in this case must not be lowered until the short circuit has reached a sufficient value to trip the substation breaker and remove power from the line. This function can be accomplished by means of an electrical interlock breaking the pantograph lowering circuit as long as the relay is energized by the short circuit current.

The third requirement is that the relay must lower the pantograph before the substation breaker is reclosed. This is not difficult to meet. Under usual operating conditions, when a substation breaker opens upon short circuit, approximately one minute will elapse before the substation operator has received instructions from the qualified supervisor and has reclosed the breaker. Since lowering the pantograph requires a time of only about one second, this can readily be accomplished.

The lowering operation, nevertheless, must be an automatic function of the relay and must be performed without unnecessary delay.

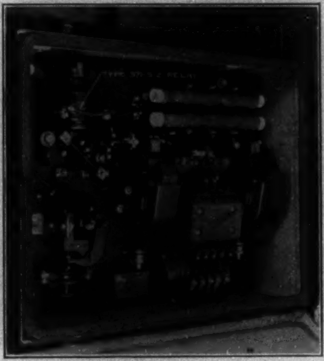

Fig. 2—Type 371S2 Pantograph Lowering Relay

Standard type in service on the Philadelphia-Paoli electrification

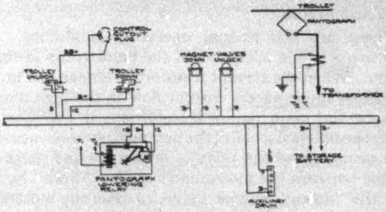

Fig. 3—Diagram of Pantograph Control Circuits Using Type 371S2 Pantograph Lowering Relay

A description of the various types of relays employed for lowering the pantograph will bring out the means by which the above outlined requirements have been accomplished.

First, we will consider the relay and its connecting circuits now in service on the Philadelphia-to-Paoli electrification of the Pennsylvania Railroad. This relay is known as "Type 371S2." Fig. 3 illustrates diagrammatically the electrical control affecting this relay and the pantograph. The pantograph is in its normal operating position. The auxiliary, or sequence drum, by which the motor switches are controlled, is in the "off" position, indicating that the motor switches are open. The pantograph may now be lowered by pressing the trolley "down" button, admitting air to the lowering cylinders on the pantograph. It will be noted, however, that by means of the 12 and 19 wires, this operation is so interlocked that it cannot be performed when the circuit has been opened by energizing the pantograph lowering relay. This gives the necessary protection to prevent the pantograph from being lowered during a short circuit. When the pantograph has been lowered, it is automatically latched by a mechanical device. It can be unlatched by pressing the trolley "unlock" button. The operating springs will then raise it to the contact wire. This operation is interlocked electrically in two places. First, the control cut-out plug must be placed in its proper receptacle by the motorman, and second, the auxiliary drum must be in its "off" position, so that the motors are disconnected.

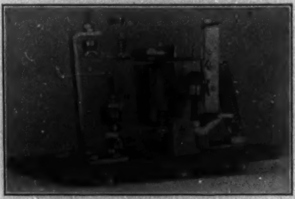

Fig. 4—Type UC-8 Pantograph Lowering Relay

These are the normal operating conditions. We now come to the operation of the pantograph lowering relay. When the current transformer shown on Fig. 3 is energized by an excess current flow in the high tension lead to the main power transformer, it energizes, in turn, the operating coil of the pantograph lowering relay. The armature of the relay is drawn up and parts the circuit between the motorman's trolley "down" button and the "down" magnet valve, so that the motorman cannot lower the pantograph and the circuit is held open for the duration of the short circuit. As soon as power goes off the trolley, by opening of the substation breaker, the operating coil of the relay is deenergized. In the meantime, the contact bearing member has been rotated by means of a spring, so that, when the armature falls back, it closes the circuit to the battery and applies current to the "down" magnet valve, thus lowering the pantograph. This supplies the automatic lowering operation of requirement No. 3, before mentioned.

When the "down" magnet valve has been energized by operation of the pantograph lowering relay, it is connected directly to the battery and remains energized. Thus air pressure is held in the pantograph lowering cylinders as long as it is available in the control air reservoirs. By this means the trolley is held down, regardless of the failure of the latching device and also regardless of an effort to raise it with the motorman's "unlock" button.

Resetting of a relay by members of the train crew is not permitted. A car on which the pantograph has been lowered by the operation of this relay, and which does not respond to the "unlock" button, is towed by the other cars in the train until such time as it can be inspected by members of the shop force, in order to determine the cause of the lowering operation.

Relays, as above described, using an electromagnet operated by current from a current transformer in the main high-tension lead and having a movable iron armature, have been in satisfactory operation up to the present time, but have proved unsatisfactory for use with high-speed breakers. A new design of this same type has recently been produced that has not yet demonstrated its ability to operate at the required speed.

To take the place of these relays, two different types have been submitted. One is operated directly by the magnetic effect of the power current passing through a surrounding iron core and eliminating both current transformer and relay operating coil. The other type utilizes current from the current transformer to operate a solenoid and plunger instead of the electromagnet and armature. Both of these devices have demonstrated, by means of oscillograph tests, that they will perform satisfactorily with short circuit current flowing in the trolley circuit for less than one-half cycle.

Reference to Fig. 5 will show the circuit arrangement for the first of these high-speed relays. This relay is known as "Type UC-8." It is composed of a rectangular magnetic core surrounding the high-tension lead, one leg of which core is pivoted along its length (see Fig. 4). This leg is slightly tilted under normal conditions to give a small air-gap. Current flow in the high-tension cable magnetizes the core, tending to close the air-gap. By means of contacts mounted on the movable leg, the same circuit relations are obtained with this relay as with the old type of relay. By the use of a laminated magnetic circuit and moving parts of low moment of inertia, it has been possible to design this relay to operate within approximately

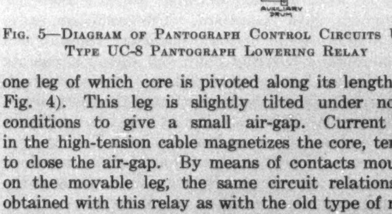

Fig. 5—Diagram of Pantograph Control Circuits Using Type UC-8 Pantograph Lowering Relay

one-third of a cycle. A typical oscillogram of this relay is shown in Fig. 6.

The second type of high-speed relay is shown in Fig. 7. It is operated by means of a solenoid plunger and is shown in conjunction with a different type of pantograph control, utilizing only one magnet valve (see Fig. 8). The magnet valve admits air to a cylinder at the pantograph, the piston of which cylinder opposes the action of holding-down springs and permits the operating springs to raise the pantograph. When air is released from the cylinder by deenergizing the magnet valve, the holding-down springs lower the pantograph. These springs are so interlinked that they overcome the raising action of the operating springs and hold down the pantograph without the necessity of an additional latching device.

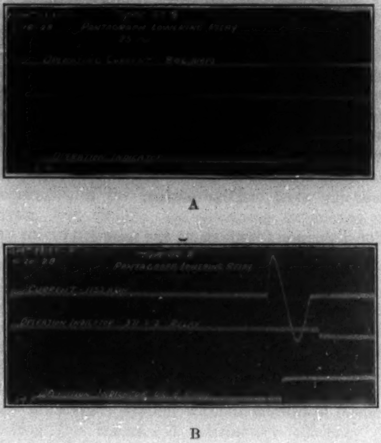

Fig. 6—Typical Oscillograms of Type UC-8 and Type 37182 Relays

a. The upper line indicates trolley current. Note that the current was flowing during only one half a cycle

The middle line traces a circuit indicating the operation of a type 37182 relay. The fact that this line is unbroken indicates that the relay did not function

The lower line is traced by a circuit through the contacts of a type UC-8 relay. The relay has operated well within the one-half cycle

b. The current flow lasted for a full cycle in this test

The type 37182 relay received sufficient impulse this time to operate. The contacts of the relay, however, did not part until after power was off the trolley

The type UC-8 relay again operated within one half cycle

An additional relay is necessary with the type of control just described. This relay is called the pantograph operating relay. The function of this relay is to hold open the magnet valve which maintains the pantograph in its extended position, against the contact wire, during normal operation.

By referring again to Fig. 8 it will be seen that, in order to keep the pantograph in its operating position, the 21 wire leading to the magnet valve must be energized and thus the pantograph operating relay must be in its latched position, as shown by the diagram. This is done by energizing the lower solenoid of the relay by means of the trolley "up" button. This push-button circuit is interlocked, as with the previously described pantograph operating circuit, so that the control cutout plug must be in place and the auxiliary drum must be in the "off" position. It is also interlocked with the pantograph lowering relay, so that the operating relay cannot be energized when the lowering relay has been tripped.

Fig. 7—Solenoid Type of Pantograph Lowering Relay

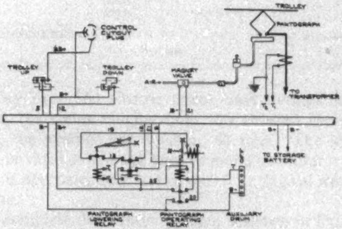

Fig. 8—Diagram of Pantograph Control Circuits Using Solenoid Type of Pantograph Lowering Relay

The normal lowering operation is performed by energizing the upper or tripping solenoid of the operating relay which trips the latch and breaks the circuit from the magnet valve wire No. 21 to the battery. Operation of the tripping solenoid is interlocked with the pantograph lowering relay, so that when the solenoid of this latter named relay is energized the circuit to the tripping coil is broken and is not closed until the pantograph lowering relay is deenergized and the 19 wire is reconnected to the 13 wire. It can be seen that, when the lowering relay is tripped, this 13 wire is connected directly to the battery and trips the operating relay immediately upon removal of short circuit current from the trolley by the substation breaker. An oscillogram showing a typical operation of this relay is given in Fig. 9.

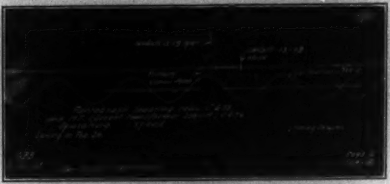

Fig. 9—Typical Oscillogram of Solenoid Type of Pantograph Lowering Relay

This type of relay has given satisfactory test results with currents from 500 amperes upward flowing for one half cycle

This oscillogram indicates successful operation with 1930 amperes flowing for 0.3 cycles on the basis of 25 cycles per sec.

In conclusion, results secured in the past with pantograph lowering relays have been satisfactory. There have been no indications that the relays have failed to function when required. Although in numerous instances the relays have operated without proper cause, these false operations have been largely eliminated by improved design and proper setting of the relay. Recently, types have been developed which are more positive in action and are less susceptible to vibration, and they have been made sufficiently sensitive and rapid in operation to be used with high-speed substation breakers.

It is felt that the additional investment required and the effort necessary to provide space on locomotives and cars for circuit breakers of proper size is unwarranted, and that such breakers may be eliminated by the installation of a pantograph lowering relay making use of the opening of the substation breaker to disconnect the electrical equipment of the car or locomotive from the line by lowering the pantograph.

## Discussion

For discussion of this paper see page 1311.

# The High-Speed Circuit Breaker in Service
## on the Illinois Central Railroad

BY W. P. MONROE[1] Member, A. I. E. E. and R. M. ALLEN[2] Non-member

***Synopsis.**—The purpose of this paper is to describe briefly the distribution system of the Illinois Central Suburban Electrification and to state considerations influencing the selection of high-speed circuit breakers for d-c. feeder and machine protection. The knowledge gained by nearly two years' operating experience with this system, which contains 98 high-speed circuit breakers, and the conclusions reached, are also presented.*

* * * * *

THE first large installation of high-voltage d-c. high-speed circuit breakers for railway service was placed in operation on the Chicago suburban electrification of the Illinois Central Railroad, in July, 1926. The reasons for the adoption of these circuit breakers for this electrification, and the results thus far obtained with them, may be of interest to those who are contemplating similar applications. With this idea in mind, the distribution system in general will first be described with special regard to those features influencing the selection of the high-speed breakers. A description of the installation and tests will then be given, and finally, the operating experience of twenty months service will be discussed.

### DESIGN FEATURES OF DISTRIBUTION SYSTEM[3]

The distribution system of this 1500-volt d-c. suburban electrification was designed to deliver current to the trains with the necessary voltage regulation, with economy in the use of copper, and with the utmost reliability. A simple system resulted consisting of seven substations conveniently spaced and feeding directly a catenary system without additional feeders paralleling the tracks. A satisfactory efficiency of distribution was obtained by the use of *tie stations* to connect the catenaries of all tracks together at various points, thus dividing the current among the catenaries over all tracks and utilizing the total copper to the best advantage.

The absence of feeders, other than the catenaries themselves and the substation connections thereto, is a factor in obtaining simplicity and in applying high-speed circuit breakers. It happened that the mechanical design of the catenary was very well suited to the conductivity requirements, this feature being partly due to the use of tie stations and partly due to the fairly close spacing of the substations.

The tie stations, besides increasing the distribution efficiency, divide the catenary system into short sections, each fed through its own circuit breakers. Because of the large number of sections and sectionalizing points of this design, remote control of the circuit breakers is necessary. The Illinois Central system makes use of supervisory control by which the power supervisor, from his desk, can open or close any circuit breaker on the system and receive indications of the opened or closed positions of these breakers at any time.

A simplified schematic diagram of the distribution system in the district having the heaviest traffic is shown in Fig. 1. It is of that portion of the system extending from the north terminus at Randolph Street to Brookdale Substation, 8.3 miles south. On every week-day over 560 electric trains pass through this district, the trains ranging from two to eight cars in length, the average car weighing 63 tons. The load factor, or ratio of average hour to maximum hour over 24 hr., is approximately 40 per cent for a typical week-day load.

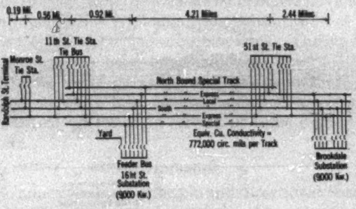

FIG. 1—SCHEMATIC DIAGRAM OF PORTION OF DISTRIBUTION SYSTEM

The complete distribution system is shown in Fig. 2.

### CONSIDERATIONS LEADING TO THE SELECTION OF HIGH-SPEED BREAKERS FOR THE SERVICE

The reliability of the distribution system depends upon adequate protection from short circuits, overloads, and other electrical disturbances. Its availability, or freedom from service interruptions, depends upon the quick isolation from the rest of the system of a section directly affected by the fault without interfering with service on the neighboring sections.

An inspection of Fig. 1 shows that in the Illinois

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[2] Power Supervisor, Illinois Central Railroad.

[3] For a detailed description of the I. C. R. R. distribution system and other phases of this electrification, see series of articles in *General Electric Review*, April, 1927.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

Central distribution system most of the sections of track are fed directly or indirectly through a large number of circuit breakers; and that if a short circuit occurs in one section, a number of other sections may be affected unless only the breakers feeding directly into the short circuited section open and isolate it. The circuit breakers, therefore, should have a high degree of selectivity in their operation.

They should also act at sufficiently high-speed to avoid serious burning of the catenary or train equipment.

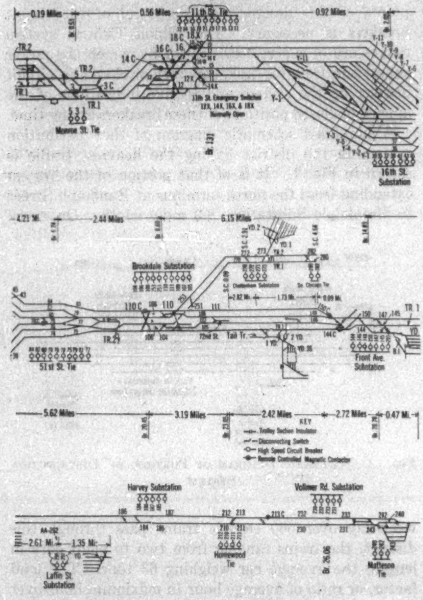
0.19 Miles
0.56 Miles
11th St. Tie
0.92 Miles
TR.2
TR.1
14 C
16 C
18 C
3 C
12X
14X
11th St. Emergency Switches 12X, 14X, 16X, & 18X Normally Open
Monroe St. Tie
16th St. Substation
4.21 Mi.
2.44 Miles
6.15 Miles
Brookdale Substation
Oakdale Substation
So. Chicago Tie
2.82 Mi.
1.73 Mi.
0.89 Mi.
110 C
110
111
TR.2
TR.1
72nd St.
Tail Tr.
1 YD.
2 YD.
YD. 35
144 C
150
147
145
Front Ave. Substation
51st St. Tie
5.62 Miles
3.19 Miles
2.42 Miles
2.72 Miles
0.47 Mi.
KEY
Trolley Section Insulator
Disconnecting Switch
High Speed Circuit Breaker
Remote Controlled Magnetic Contactor
Harvey Substation
Vollmer Rd. Substation
186
187
184
212
213
210
211
213 C
232
233
230
231
242
240
243
AA-282
2.61 Mi.
1.35 Mi.
YD
Laflin St. Substation
Homewood Tie
Br. 26.06
Matteson Tie

FIG. 2—COMPLETE SCHEME OF DISTRIBUTION ON THE ILLINOIS CENTRAL RAILROAD

They should be adapted to remote control since many of them will be in unattended stations and all must be under direct control of the power supervisor's office.

Their reliability should be such that they will not require very frequent maintenance attention.

The Commonwealth Edison Company of Chicago and affiliated Public Service Company of Northern Illinois own and operate the substations feeding the Illinois Central distribution system, and also own and maintain the feeder circuit breakers in the substations. The operation of these breakers, however, is of great importance to the railroad because they form a part of the distribution system and must act in conjunction with the tie station breakers. The Edison Company and railroad engineers, therefore, worked together in selecting the type of circuit breaker and protection scheme used in the substations.

A study of the merits of all proposed 1500-volt d-c. circuit breakers, including extensive factory tests, resulted in the selection of the General Electric type J R high-speed circuit breaker for the service, and this type is used in all section feeders at all substations and tie stations (Fig. 3). They are also used in both positive and negative leads of the synchronous converters in substations. The detailed theory of action of this breaker has been previously described before the Institute.[4]

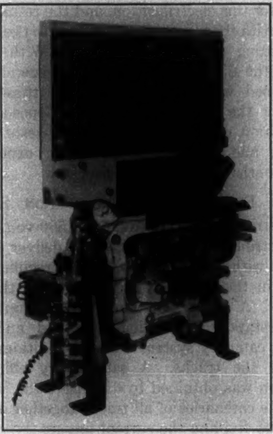

FIG. 3—HIGH-SPEED BREAKER UNMOUNTED

## INSTALLATION AND INAUGURATION OF SERVICE

The most modern type of construction was used in the installation of the circuit breakers in both substations and tie stations. Each high-speed breaker is mounted on its own truck with control panel, and spare trucks with breakers are available so that repairing is made easy by the removal of the bad order circuit breaker and truck to be repaired and replacing it with a spare truck containing a spare circuit breaker. The circuit breaker trucks can be interchanged readily in the tie stations and in the substations, but an attempt is made always to keep each breaker in the same feeder. Although most of the parts are interchangeable, a complete tie station breaker cannot be interchanged with a substation breaker, because the holding coil of the tie station breaker is energized from 1500 volts while that of the substation breaker is energized from the substation 125-volt d-c. supply.

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[4] *The High-Speed Circuit Breaker in Railway Feeder Networks*, by J. W. McNairy, TRANS. A. I. E. E., Vol. XLV, 1926, p. 962.

Automatic reclosing features are a part of the control of the tie station breakers, but the closing of substation feeder breakers is governed entirely by supervisory control. Both tie stations and substations are equipped with transfer buses so that in emergencies two or more sections can be fed through the same circuit breaker.

The calibration of the feeder circuit breakers was made at the factory. The settings of the tripping points, however, were precalculated by the railroad company's engineers, and the breakers were set accordingly during the installation. In order to make sure that the predetermined settings were right, a number of short circuit tests was made at the completion of the installation and when power was available at the d-c. buses of the substations. A test car was equipped so that short circuits could be applied at any point, and an oscillograph was installed in the car to record the short-circuit currents and time characteristics of the circuit breakers.

The first tests were made at the Homewood tie station, in an outlying district, where short circuits were applied to the catenary at a point very close to the tie station. It was found that the selectivity of the circuit breakers in isolating the fault was very satisfactory. Tests were also made at 11th Street tie station, one of the largest tie stations in the system, and in this case also the selectivity was satisfactory with the predetermined settings, but some minor adjustments were found to be necessary. Similar tests were made at the other tie stations and substations. In this way the system was "tuned up" for safe and correct operation of circuit breakers. In only a few cases was it deemed advisable to change the predetermined circuit breaker settings.

In the two-track district between Front Avenue and Harvey substations, there is no tie station, (see Fig. 2). It was found that the rate of current rise at one of the Front Avenue substation feeder breakers was not sufficient to open it when a short circuit was applied near the Harvey substation, although the Harvey substation end cleared satisfactorily. The short-circuit current in this case is limited to a maximum value of approximately 3500 amperes by the resistance of the line. The predetermined setting of the Front Avenue breakers was 4000 amperes, but it had to be reduced to 3500 amperes to insure protection. Since the breakers feeding the district south from Brookdale substation to Front Avenue substation, and those feeding north from Harvey substation to Front Avenue have the same feeding distance without tie stations, their settings were also lowered to 3500 amperes. Later, the manufacturers altered the design of the inductive shunt for these breakers, changing both resistance and inductance, so that the settings could be raised to 4000 amperes with ample protection. These circuit breakers with low settings are now all equipped with the new shunts and the settings readjusted to 4000 amperes accordingly. Since the accelerating current of a ten-car multiple unit train approaches 4000 amperes the setting at 4000 amperes (for straight overload) seems to be low to prevent circuit breaker openings from the useful load. Actually, the breakers are sometimes opened by the load, and as traffic increases, the openings will increase. It has always been the intention of the railroad to build a tie station in each of these districts when the traffic so demands.

These preliminary tests on the distribution system have proved the advisability, if not the necessity, of thoroughly trying out a distribution system of this kind before regular service is started. As a further precaution, when the I. C. R. R. electric suburban service was fully inaugurated in August, 1926, emergency operators were stationed in the most important tie stations during the rush hours to take care of any failure or faulty operation of the circuit breakers. The necessity for this latter precaution was not proved, however, since no serious troubles developed.

## RESULTS OF TWENTY MONTHS OPERATING EXPERIENCE

Since August 1926, the high-speed breakers have been in continuous service handling the dense traffic of the Illinois Central electrified suburban lines. During this period, there has been opportunity to observe their performance under varying conditions, and there are presented herewith brief comments on certain features of the actual operation in service of these high-speed breakers.

### ADVANTAGES

The inductive shunt principle and directional characteristics of the high-speed circuit breakers make automatic isolation of trouble by selective operation simple and almost 100 per cent.

The high-speed operation reduces to a minimum the damage to train equipment and overhead. In fact, the burning is so slight that in most cases it is difficult to locate by inspection a traction motor which has flashed over. In no case has the damage by a single flashover been sufficient to necessitate taking a motor out of service.

With a lapping section insulator, such as is used on the Illinois Central, more or less burning is caused by a pantograph moving over a section insulator, one side of which is alive and the other side temporarily grounded by a short circuit or for some other reason. High-speed circuit breakers reduce this burning to a minimum. A recent communication from the Victorian Railways of Melbourne, Australia, which is in the process of changing to high-speed circuit breakers on their 1500-volt d-c. electrification, states that trouble from this cause has been considerably reduced thereby. Their report bears out the experience of the Illinois Central.

Care of the high-speed circuit breaker contracts has been found to be almost unnecessary, due to the secure manner in which they are held together magnetically, instead of relying on a spring and latch arrangement.

In the early stages of electric operation, there was a very large number of automatic circuit breaker openings for which there was no visible cause. Many of these were due to overhead or train equipment troubles which occurred periodically and the small amount of burning made it impossible to locate the fault by ordinary inspection. Others were known to be due to motor flashovers caused by wheels slipping on wet rails; this is now avoided by proper handling of the trains by motormen.

To trace recurring troubles, a systematic record of automatic circuit breaker openings is kept. For each automatic opening a notation is made in this record of the train in the trolley section, the numbers of the motor cars in the train, location of the train, and the name of the motorman. The following results were and are obtained from the study of periodic summaries of this information:

1. Motor flashovers due to slipping of wheels was confined to a few motormen. These motormen were given special instructions and motor flashovers from this cause have been reduced from about thirty per month to about three per month, and the damage is almost negligible.

2. If an unusual number of circuit breaker openings is found to occur at times when trains are passing a certain point, a thorough inspection of the overhead is made, which usually results in the discovery of a catenary defect at the location.

3. Car equipment trouble is shown by an excess of circuit breaker openings marked against a particular car and this car is taken in for inspection. These inspections invariably verify the evidence shown by the automatic opening report.

It is believed the tracing of these faults before serious damage results is made possible by the high speed characteristics of the circuit breakers.

### DISADVANTAGES

There is theoretically an inherent defect in the high-speed breaker characteristics as applied in this service with a short circuit occurring at the time of heavy traction load. When the circuit breaker is carrying heavy current in the right direction for its operation and a short circuit occurs on an adjacent section not directly fed by the breaker, there is a possibility of the breaker opening automatically and incorrectly from the selectivity standpoint. This incorrect operation is due to the load current superimposed on the short-circuit current, the effect being to lower the critical rate of current increase which will open the breaker on short circuit. Actually there have been very few incorrect automatic openings of circuit breakers which have been traced to this cause.

The setting of high-speed circuit breakers on the Illinois Central is accomplished by turning a one-inch iron screw in or out of the holding coil core, thus varying the reluctance of the holding coil magnetic circuit. A marked brass calibrating plate serves as a scale. Such a method of setting is not very accurate considering that highly selective operation is expected. Also, a circuit breaker truck must be removed from the circuit in order to change the setting.

The breaker setting is changed somewhat by the wearing of the main contacts, and periodic calibrating will probably be necessary. Such calibration would require artificial loading which would be cumbersome with 5000- or 6000-ampere settings. However, this will be an infrequent procedure.

Although its advisability may be questioned, it is a practise of most operating companies to relieve traffic congestions by holding carbon circuit breakers closed for a short time. The high-speed circuit breaker does not permit this practise and three cases of breakers opening on legitimate load on the Illinois Central have resulted in serious delays.

It is sometimes desirable to burn clear a minor short circuit. This is almost impossible due to the high-speed operation. In one case, a No. 12 A. W. G. meter lead grounded to the meter frame and could not be burned clear. This occurred on a test train previous to regular operation, but could have caused serious delays had it occurred in regular service, since it was difficult to locate.

The injurious effects of the high-voltage surges induced by the high-speed operation have sometimes been cited as a disadvantage of the device. These surges on our system amount to approximately double the line voltage and are greater than the surges due to openings of carbon circuit breakers. There has been no direct evidence of damage caused by these surges on the Illinois Central.

A number of minor changes in design of the high-speed breakers has been effected since the original installation. These alterations were made by the manufacturers to correct faults which developed under operating conditions. As an example, considerable trouble was experienced by the breakers pumping, due apparently to bouncing of the armature against the core. This pumping often resulted in the reset coil burning out. A change in design of the reset coil core has corrected this defect.

The reset coils of the present high-speed breakers seem to be designed with only a narrow margin of safety as regards operating temperature, since they will reach dangerous temperatures if operated at too frequent intervals. A more liberal design of coil would correct this disadvantage.

Two serious substation bus short circuits were experienced, which may have been due to insufficient clearance of the sheet metal enclosure of the breaker mechanism. The circuit breakers are now being mounted on an ebony asbestos base, instead of metal, and no further trouble is expected. It is understood the manufacturer is incorporating this change of design in all new high-speed circuit breakers.

It was necessary to raise the overload setting and to remove all but $\frac{3}{8}$ in. of the iron on the inductive shunt of the positive machine breaker in the substations, which was set for a low value of reverse current. A sudden interruption of current in the normal direction (such as opening of a feeder breaker) causes a reverse flow of current in the bucking bar due to the collapse of magnetic flux in the inductive shunt, the effect being to open the breaker unnecessarily. The changes in the setting and inductance of the shunt obviate this difficulty.

It is concluded that the disadvantages in this case may be said to be minor defects and there is no doubt that the high speed breaker has contributed much to the success of the Illinois Central electrification.

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## Discussion

### PAPERS ON ELECTRIFIED RAILWAYS

(McNairy, Wilcox, Bardo, Morton, Brown, Monroe and Allen)

Denver, Colo., June 27, 1928

**H. C. Graves:** Mr. Wilcox mentions selective relaying equipment as a necessary adjunct to the breaker described in the paper presented by him. I should like to outline the system conditions obtaining on an actual, typical system, which made simple over-current tripping means inadequate, to describe the application of high-speed relays, and to give test results which illustrate the adequacy of the protective relay equipment used.

The four-track railway system connection is shown at the bottom of the accompanying Fig. 1. The four 11-kv. contact lines are sectionalized at each feed-in substation, which are located at approximately equal intervals. Each 11-kv. substation bus is fed by high-tension feeders through one to four transformers depending on load conditions. The generating capacity feeding into the high-tension feeders through transformers, may vary from one to eight generators. The impedance of the high-tension feeders is negligible as compared to the impedance of generators, transformers, and contact lines.

Short-circuit conditions existing on this system are as shown at the top of Fig. 1. Since the high-speed relays must operate within 0.01 sec., or $\frac{1}{4}$ of the cycle, after the relay setting is exceeded, they must frequently operate under asymmetrical current conditions. For this reason, the maximum current condition which must be considered is the maximum instantaneous asymmetrical condition. These maximum values of current which operate the relay on the faulty line, for example at bus *A* in Fig. 1, are shown in Curve 1 ranging from 24,000 amperes with a fault located just outside of the breaker near the bus to 2700 amperes when the fault is at the opposite end of the line. Minimum values of fault currents will exist when the fault occurs at a time which causes symmetrical conditions of current to exist, and when the generating capacity is a minimum. These currents are as shown by Curve 2. The ratio between maximum fault currents to minimum currents with all breakers closed is seen to be approximately 6 to 1.

During fault conditions, some currents will flow in unfaulted contact lines and tend to cause operation of their protective relays. Curve 3 shows how these currents vary for a particular operating setup. Under these conditions the line relays must not cause tripping.

Using these curves as a basis for determining the type and setting of protective relays it may be seen that instantaneous over-current relays cannot be applied to protect against all conditions because: (1) Under minimum operating conditions they must clear with 1700 amperes flowing into each end of the line, the fault being in the middle; or if the fault occurs at one end of the line the breakers must clear with 4200 amperes flowing at that end but only 600 amperes flowing at the other end. This is shown in Curve 2. (2) Under certain conditions, as shown in Curve 3, 2700 amperes may flow in the unfaulted line which must not cause clearing. If the relays do operate under this condition, a total of 16 breakers may open, two of these alone being sufficient to clear the faulty line. (3) To the fault current in the unfaulted line may be added load current of 1200 amperes which still must not cause clearing.

Thus the relay system must operate with only 600 amperes flowing in a faulted line and must not operate with 3900 amperes flowing in an unfaulted line in order to assure perfect selectivity. Further calculations also show that with a fault near one end of the line, the breaker nearest the fault being open, the current flow through the other end may be only 1900 amperes and the relay must operate under this condition. Simple over-current relays are obviously not applicable.

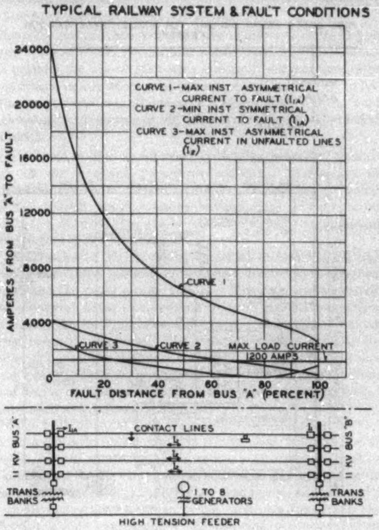

Fig. 1

In order to secure all the advantages of the high-speed breakers, cascading or sequential operation of breakers should be avoided. This is a function of the relay system.

One suitable system of protection could be built around pilot wires. An objection to this system is found in the cost and maintenance. A second suitable system involves installing reactors in series with each breaker so that the current in the faulty line is always larger than that in the unfaulted lines. The reactors create an unbalanced current so that even with the fault just outside of the bus, relays can be made to discriminate on the unbalance. The objection to this system lies in the cost and increased voltage drop and losses due to the line reactors.

In either of the above systems provision must be made for suitable compensation for normal load currents.

A relatively inexpensive scheme of protection has been devised to give 100 per cent selectivity which permits cascading for only a very small percentage of the contact line length. It does not necessitate line reactors or pilot wires, and works from standard current and potential transformers. The relays operate in from 0.001 to less than 0.01 sec. from the time when the relay setting is exceeded.

The scheme is built about a relay which is independent of connected generating capacity. This is an over-current relay, instantaneous in its operation, which has a current setting dependent on the bus voltage. With a fault located at a definite point on a contact line, the ratio between voltage and current, which determines the operating point of this relay, is a constant. Thus the relay is equivalent to an impedance-measuring device and can therefore be set to operate for any faults within a certain distance from the breaker. The sensitivity of this relay is such that in practise, it is set to operate with faults located within 90 to 95 per cent of the contact-line length.

HIGH SPEED RELAY SCHEME FOR SINGLE PHASE RAILWAY FEEDERS

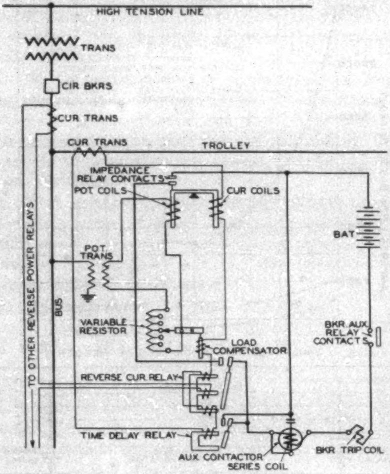

FIG. 2

With faults near one end of the line, the current through the other end of the line will be small, and will correspond to approximately 600 amperes or one-half of the maximum normal load current. However, the voltage on the relay at the far end is low so that the relay will operate. Thus this device will not operate on 1200-ampere load current but will operate on a 600-ampere fault current or even less.

When a load is connected just outside of one breaker, it will effectively change the impedance of the line when faults occur at the opposite end of the line. Its effect is to reduce the impedance to the flow of current through the breaker and thus increase the likelihood of the relay operation. Therefore, in order to avoid faulty operation a presetting device has been added which changes the impedance setting of the relay depending upon the amount of load in the circuit. The diagram in Fig. 2 shows how this setting change is effected. The load presetting relay cuts out resistance, normally in series with the potential restraining circuit of the impedance relay, as the current in the line increases. Thus when loads are located on this line near the station the effect of the potential coil is comparatively large. As this load travels along the contact line toward the other station the load presetting relay slowly changes the amount of resistance in series with the potential coil so that the relay will always operate, independently of load conditions, with all faults located within 90 to 95 per cent of the distance to the next substation.

INSTANTANEOUS DIRECTIONAL RELAY CHARACTERISTIC

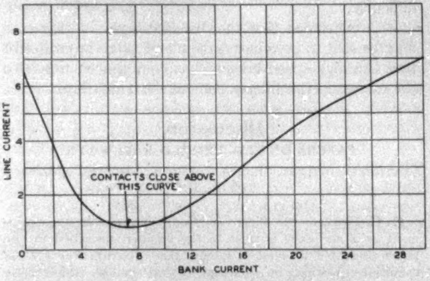

FIG. 3

FIG. 4

As is the case with all impedance devices, a directional relay is desirable. An induction disk, or integrating device, cannot be used for this application since its time of operation is entirely too long. The principle of operation of the device used for the directional feature depends on the fact that the current through the transformer bank at a station is very nearly in phase with the current flowing in the line. As a result, the relative directions of the instantaneous current values can be used for determining the direction of operation of a polarized relay. The transformer-bank current polarizes the relay as shown in Fig. 2, and the direction of operation of the relay then depends on the line current. The relay is very fast in operation under any fault condition that can cause operation of the impedance device.

The characteristic curve of one of these relays is shown in Fig. 3. The relay has been made to operate with current in the line alone so as to be independent of whether the transformer bank is connected in the circuit or not. Adjustments on the relay permit the relay to operate at any value of line current alone, which may prove to be desirable in a particular application.

Mention has been made of the fact that this impedance relay will operate for 90 to 95 per cent of the line length, and will not operate with faults just outside of the station at the opposite end of the line. However, in that case, the impedance relay at the fault end of the line will cause quick clearing of the breaker at that end, and thus leave only the breaker farther from the fault to feed into the fault. As soon as the breaker at the fault is open, the current through the breaker at the far end of the line increases to such an extent as to permit operation of a time-delay overcurrent relay. This relay operates after a time delay of approximately 1¼ cycles to cause clearing of this breaker. Thus, the sequence of operation for faults in the area where simultaneous operation is not obtainable, is that the breaker immediately adjacent to the fault opens instantly due to the impedance relay, and then the breaker at the far end of the line opens due to the operation of the time-delay relay.

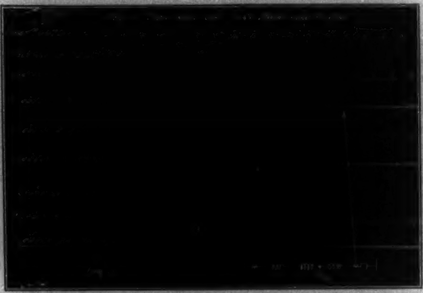

Fig. 5

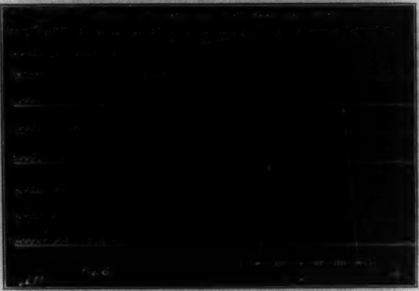

Fig. 6

In order to determine the efficacy of this system of relaying, a test setup was made. The diagram of connections is similar to that shown in Fig. 1 and the short circuit currents are as illustrated. Fig. 4 illustrates an oscillogram which was taken on this test system. The transformer currents and line currents are shown on the oscillograph record, the arrows from the diagram indicating each particular current. The voltages on the busses at each end of the circuit are also shown. Element No. 2 represents the current flowing through the trip coil of the breaker closer to the fault in this figure and Element No. 7 represents the current in the trip coil at the far end of the faulty line. As may be seen from the operation of Element No. 2, the trip coil of the breaker at the fault was energized immediately on the occurrence of the line trouble with the result that the heavy current was cleared in approximately ½ cycle. The trip coil of the breaker at the far end of the line, as shown in Element No. 7, was energized approximately 1¾ cycles after the fault occurred. This fault was taken in a position such that sequential operation of breakers was necessary. Figs. 5 and 6 represent faults at different points along the contact line. The oscillograph elements are the same as shown in Fig. 4. The total time of clearing for Figs. 5 and 6 was less than 1 cycle, and simultaneous operation of the breakers occurred. It is to be noted that the trip coils of the breakers at both ends of the line were operated almost simultaneously.

Thus, the use of a breaker with trip magnets permits the use of any type of relays desirable for any particular installation. This permits the use of pilot-wire schemes, line reactors, impedance relays, or any other relay system which seems best to fit a particular application. It permits system changes to be made which necessitate changes in the relay system at a comparatively small cost.

The scheme of high-speed relay protection described includes many of the standard protective schemes. The relays are modifications of those commonly used. The experience gained with this system would seem to indicate that any commonly used system of protection can be modified so as to be applicable for high-speed breaker operation.

**F. C. Hanker:** Mr. McNairy raises an interesting comparison as to the relative inductive influence produced by a-c. railway circuits and the usual power circuits. The only important difference between these two systems from an inductive-coordination aspect is the fundamental-frequency induction from the normal operating currents. The induced voltages from an a-c. railway system are due almost entirely to the earth return loop. In the case of faults to ground, the essential difference is only one of degree and not one of kind, assuming the power system to be grounded as is normally the case.

On the basis of equal fault currents on an a-c. railway system and on a 60-cycle power system, the induced voltages for the 60-cycle system would be approximately 10 times as great as for a fault on the 25-cycle system. This is due in part to the higher coupling factor at the higher frequency, and in part to the small earth current, which in the case of a four-track electrification is only approximately 25 per cent of the total return current, the rails carrying 75 per cent of the return. In the case of the electrification mentioned by Mr. Graves in his discussion of Mr. Wilcox's paper, the total fault current flowing from one station to a fault at an adjacent station is approximately 10,800 amperes. The 60-cycle current causing the same induced voltage would be $\frac{10{,}800}{2.4 \times 4} = 1125$ amperes, a value which is exceeded on many power systems for faults to ground. It is important to note that in the case of the railway system, the induction in sections not adjacent to the fault will be negligible. This is by no means true in the case of power transmission systems where the fault current will be of substantially the same value for parallels of several times the length of a normal railway distribution section.

Mr. McNairy makes the statement that the induced voltage from railway systems will be more frequent and of greater magnitude than the disturbances set up by an ordinary power circuit.

While it is undoubtedly true that such disturbances will occur with greater frequency on a railway system, we feel that the voltage for an equal exposure will be higher for the power system. Therefore, the only way in which we can reconcile Mr. McNairy's statements is on the basis of unequal exposures.

It seems to us that the outstanding factor in the coordination problem arising from a railway electrification is due not to the peculiar characteristics of the electrification system, but principally to the severe exposures which were created early in the development of the railway and communication services before the coordination problem was appreciated.

We note that Mr. McNairy states that a breaker and relay system designed for one-cycle operation will be the most desirable from an inductive-coordination standpoint. An effort to produce a faster breaker would probably cause undesirable transient induced voltages. This has been the basis of the design of all our high-speed a-c. circuit breakers, including the original New Haven breaker designed in 1922.

In Mr. Grave's discussion of Mr. Wilcox's paper it was brought out that on an actual system there were certain conditions of minimum generating capacity which required breaker operation on currents as low as 600 amperes or less, while under maximum conditions the breaker should not open on currents as high as 3900 amperes, this value being the sum of load current and current flowing to the fault in the good lines. That is, at the remote end of four parallel lines the faulted line may be carrying a current of 2700 amperes, the trolley with load may have a current of 3900 amperes, and the other two unfaulted trolleys may be carrying a current of 2700 amperes. Under minimum generating conditions, the faulted trolley current will be 600 amperes or less, the loaded trolley 1800 amperes, and the other two unfaulted trolleys 600 amperes. Under such conditions, will the protective system described by Mr. McNairy prevent the loaded and unfaulted lines clearing before the unloaded faulted lines? This situation would appear to be even worse if there are only two contact lines in service. It would appear that if the tripping point is set high enough to avoid clearing the loaded unfaulted lines, even sequential action could not be depended upon to clear the faulty line in such a case as Mr. Graves points out, since even after the breaker at the faulted end of the line has opened, the current at the other end may not exceed 1900 amperes. It may be possible to proportion the loading and saturating resistors to cover such a range. I should like to hear some quantitative data from Mr. McNairy on this point.

The trip-coil currents plotted by Mr. McNairy in Fig. 4 are based on a symmetrical short circuit. The duration of the first loop of current is frequently more than ½ cycle, and from his equations it would appear that if we assume $y = 45$ deg., the trip-coil current would pass through one of the flat spaces shown in the figure before having its first initial rise. This would mean that there would be no distortion in the holding magnet until the second current loop, which would mean more than ½ cycle delay before the breaker starts to open. Further, there is some doubt about Eq. 9 and a later one which make it difficult to predict what the effect of an unsymmetrical short circuit would be, and it would therefore be desirable to ask Mr. McNairy to explain further this phenomenon regarding an unsymmetrical fault.

**Sidney Withington:** It is of considerable interest that the apparatus described by Mr. Bardo, which represents the first examples of its type to be placed in commercial operation, should have proved so successful. The circuit breakers were built, as Mr. Bardo says, after some hesitation on the part of the manufacturers, who perhaps naturally were not enthusiastic in making development of this nature which the quantity then immediately in sight did not apparently justify placing upon a manufacturing basis. Subsequent demands are, however, an indication of the value of this type of equipment and the expense of this initial development has undoubtedly been warranted.

The operation of these circuit breakers has on the whole been very satisfactory, especially considering the fact that they represented a type of apparatus of rather radically novel design as compared with circuit breakers previously available. The difficulties which have been experienced were mostly of a minor nature and in practically all cases did not prevent proper clearing of the circuit. In most of the instances a minor revision in design has prevented a repetition so that in the future even better records may be confidently expected.

The installation has been of value in that by quickly clearing grounded circuits inductive effects on closely paralleling communication circuits have been prevented without consideration of booster transformers or other undesirable apparatus, and damage to the power distribution system on account of arcs at the point of fault has probably, in some instances at least, been eliminated.

It is entirely probable that on account of the obvious advantages in quickly clearing a circuit disturbance the use of high-speed circuit breakers may be expected to increase rapidly with the extension of heavy traction electrification.

**P. H. Hatch:** The problem of adequate circuit-breaker protection for electric locomotives and cars operating on the a-c. single-phase system is becoming more and more important as the magnitude of power supply is increasing. As Mr. Brown pointed out, sufficient space is usually unavailable on rolling stock to accommodate a circuit breaker capable of rupturing a dead short circuit. This has meant, on most electric railroads using a-c., that what circuit breakers have been supplied are used essentially as oil switches. Some method, therefore, must necessarily be developed for protecting locomotives or cars against the disastrous effects of short circuits occurring in the high-tension apparatus or wiring. On the New Haven, this has taken the form of a time-element relay so adjusted that the circuit breakers on the locomotives or cars, in case of short circuit, will not operate until sufficient time has elapsed for the sectionalizing breakers in the feeder and trolley circuits to trip.

It would seem that some arrangement for isolating a short circuit on a unit of rolling stock might be developed which would combine the advantages of lowering the pantograph automatically and at the same time introducing a definite time element between this operation and the appearance of the short circuit, which would give the sectionalizing breakers time to act. Hence, if for any reason the sectionalizing breakers have failed to act and the short circuit hangs on, the locomotive or car will be isolated. This, of course, involves the possibility of the power arc burning the overhead line in two, but where safety of personnel might be affected, this feature could easily be risked.

Referring again to Mr. Brown's paper, the development and application of high-speed circuit breakers for controlling the power supply introduces the problem of obtaining a relay sufficiently sensitive to operate when the current to the section affected is broken in less than a cycle's time. This has been very adequately dealt with in the paper referred to.

It takes little imagination to understand the many advantages of interrupting a short circuit before it has reached dangerous proportions. The general application of high-speed current-rupturing apparatus should go far toward simplifying the problem of protecting locomotives or cars. This will result in increased safety to operating personnel as well as substantial decrease of material damage.

**J. W. McNairy:** Mr. Wilcox's paper makes a statement that, with high-speed d-c. breakers, limitation of the magnitude of the short-circuit current is the only important factor in preventing flashover. I inferred from his statement that, in his opinion, the width or duration of the peak of the current curve, as shown by oscillogram, is of no importance. In this connection, I am particularly concerned with the synchronous converters when fed through a-c. lines of considerable reactance, where the short-circuit current is supplied largely from the kinetic energy of the machines. Limitation in the amount of kinetic energy taken out, (and the rate is high at excessive currents), is of considerable importance in preventing flashover because of the unbalance in armature reactions.

I should like to ask also if it is not practically impossible to stop the current rise on short circuit below the commutating value of a machine, making it, therefore, necessary to limit the time the current is above the commutating value to less than the length of time required for an arc to be carried by a commutator segment from one brush to another.

In the paper by Messrs. Monroe and Allen I wish to comment on the statement that the calibrating means, using reluctance in the magnetic circuit, is not as accurate as it should be. I should like to ask Mr. Monroe whether he feels that the inaccuracies are due to the use of the principle of magnetic reluctance, or are due to the method of utilizing the principle in present designs. I also inquire as to whether he has encountered sufficient inaccuracies from such a source to upset selective operation on this system.

Another comment I should like to make is on the statement that it is not possible to hold the high-speed breakers closed where it is desirable to burn off short circuits. A simple method can be provided with breakers of this type whereby an operator by means of an emergency button can increase the holding-coil strength to any desired value, and thereby obtain any tripping value desired for emergency conditions. Such a system may, of course, be operated by supervisory control.

One further statement I am interested in is that with reference to the high-voltage surges induced by high-speed operation, that is, that a voltage approaching twice normal may result across the circuit breakers in the d-c. circuits when operating. I believe this is a normal phenomenon with any type of circuit breaker.

When the short circuit occurs at the end of a feeder and is opened at the substation end, the inductive voltage of the feeder is opposite in polarity to the normal system voltage. While an oscillogram of the voltage across the contacts of the breaker will show double voltage, the voltage of the feeder in front of the substation changes from plus to minus, the actual voltage not being appreciably above the rating of the system.

A more important case is the operation of the circuit breaker on a locomotive where the voltages are additative. These need not be high-speed—any of the usual types of breakers may give voltages in the same order of magnitude as the high-speed breaker. This is particularly true since the high-speed breaker is effective in limiting the short-circuit current to a value much smaller than the short-circuit value, and it is, therefore, possible to break the circuit in less time because of this lower initial current.

**Caesar Antoniono:** In Mr. Wilcox's paper the statement is made, "Where feasible, a solid butt contact without auxiliary arcing tips becomes very desirable, etc."

That is a point about which I disagree with Mr. Wilcox. I don't think that a solid butt parallel contact as described in this paper is practical. When the breaker opens there will be arcing and burning at the top of the contacts. Any blisters that are caused by the arc will affect the alinement of the contact.

If there is any disturbance of alinement you have to cut the face down and in the field this takes a long time. For that reason I claim that the breaker is not practical from an operating point of view.

In Mr. Monroe's paper, which covers a different design of breaker, there is the statement, "Care of the high-speed circuit breaker contacts has been found to be almost unnecessary." That is a practical breaker from an operating point of view. In the same paragraph it says, "Due to the secure manner in which they are held together magnetically, instead of relying on a spring and latch arrangement." We find at times it is desirable to have the latch breaker rather than the magnetically held, for the reason that on interurban service, where interruptions of power are likely to occur very often, magnetically held breakers will open and then there is trouble in reclosing under low-voltage condition before the voltage is reestablished. Therefore, from experience I believe that there are conditions under which the mechanically latched breaker is preferable.

**D. C. West:** The term "high-speed" is relative, and assumes a finite meaning only when referred back to some standard of comparison. Since the real necessity for a d-c. high-speed breaker lies in the protection of 60-cycle synchronous converters, the speed required to protect such a machine, on dead short circuit across its d-c. terminals, is quite generally accepted as the criterion in d-c. practise. This has established the nature of present commercial designs, and the resulting breakers are capable of considerably higher speed than that which will provide quite adequate protection for other classes of conversion equipment, for motive equipment, or for d-c. distribution systems.

In order to understand the necessity for the very high speed required to protect a 60-cycle synchronous converter, consideration must be given to the inherent characteristics of the machine itself. It must also be borne in mind that although the 25-cycle converter possesses the same fundamental characteristics, the 60-cycle machine is considerably more susceptible to flashover because of its much more restricted design possibilities. The idea seems to be quite prevalent that a high-speed breaker protects a synchronous converter solely by virtue of the facts that it limits the ampere-seconds in the d-c. short circuit, considered from standpoint of heating under the brushes, and that it limits the peak value of current to be commutated. While these are undoubtedly important factors, the major effect is in the limitation of the angular displacement of the rotor from its no load phase position. Under normal conditions, the a-c. and d-c. components of current in the armature windings are opposed, and of such relative magnitudes that the resultant average armature reaction is approximately 15 per cent of that in a corresponding d-c. machine. The design constants of the machine affecting commutation are necessarily proportioned accordingly. On the sudden rise of d-c. incident to a short circuit, however, the machine acts temporarily as a d-c. generator, taking its energy from the inertia of the rotor. The a-c. builds up and supplies energy to the short circuit only as the rotor delivers its energy and drops back in phase position. This results in a temporary unbalance of the a-c. and d-c. components, with the latter greatly predominating and setting up a high armature reaction. Then when the d-c. is suddenly interrupted there is a large unbalance in the opposite direction, due to the fact that the a-c. continues to flow in proportion to the angular displacement of the rotor at the time the d-c. circuit is opened. The energy component of this follow-up a-c., which tends to restore the rotor to its no-load phase position, results in an excessive armature reaction since there is no opposing d-c. component in the armature windings. It is this armature reaction which, in most cases, is principally responsible for flashover of synchronous converters. In other words, such a machine will successfully commutate, for short periods, very large values of direct currents which, if too suddenly interrupted, will cause the machine to flash over.

The high-speed breaker must, then, limit the amount of energy taken from the rotor, and hence the angular displacement at the time of interruption, to such a value that the interruption of the d-c. circuit will not result in flashover. In speaking of d-c. high-speed breaker performance, the time to the point of current limitation, which with a given machine and circuit determines the peak value of current, is a better indication of its protective ability than is the time for total interruption. In fact, it would be preferable, having limited the current within a certain time, to reduce the current quickly to a value corresponding to the rotor phase displacement, and then reduce it very slowly to allow the rotor to recover at approximately the same rate and therefore maintain more nearly balanced relations in the armature. This is an impossible characteristic since the high magnetic blow-out effect which, as the author has explained, is necessary for high-speed limitation, also produces a high current decrement. It is possible to obtain the same effect, however, by applying the breaker to shunt a current-limiting resistor in series with the machine. Opening of the high-speed breaker then reduces the current to a value as determined by the resistor, usually two to three times machine rating, and the circuit is then interrupted by another breaker of ordinary speed.

Mr. Wilcox has pointed out the rather narrow design limitations which are imposed by the necessity for extremely high speed in the protection of 60-cycle synchronous converters. In order to provide protection under all operating conditions it is essential that the breaker be capable of this speed on *OCO* as well as on *CO* cycle. The design could be materially simplified by sacrificing a few thousandths of a second in speed on *OCO* operations, but the machine would not be protected in the case of the breaker being closed in against a short circuit. The breaker shown in Fig. 1 of the paper by Mr. Wilcox, was recently tested by the Commonwealth Edison Company at Chicago. The accompanying Figs. 7 and 8, show the oscillograph record of two of these tests in which a dead short circuit was applied to a 3000-kw., 600-volt, 60-cycle, 400-rev. per min. synchronous converter. Fig. 7 shows an *OCO* cycle and Fig. 8 shows a *CO* cycle. Within the accuracy of scaling values from the oscillogram, the speed and peak value of current are the same in both cases. The current was limited to 435 per cent of machine rating in 0.075 sec. and was completely interrupted in 0.014 sec.

**J. B. MacNeill:** Mr. McNairy discusses frankly the relative merits of oil and air circuit breakers as applied to contact-line service. I should like to add a few points to that discussion.

1. Regarding the effect of repeated operations on the two types it should be pointed out that it is the depreciation imposed by the short circuit on the breaker which determines its fitness for further service rather than any inherent quality of the design. The air breaker described by Mr. McNairy will open repeated short circuits. A properly designed oil breaker such as described by Mr. Wilcox will do the same. Each device, by reducing the duration of arcing to approximately one-half cycle, at the same time reduces the depreciation of the structure, whether this be oil depreciation, contact burning, or arc-chute charring. Without doubt, proper oil breakers will give service continuity and maintenance cost comparable to air breakers.

2. The space required by the air breaker seems to be considerable. Fig. 2B would indicate a length of approximately 12 ft. and a height of approximately 10 ft. 6 in., or a volume of approximately three times that of a comparable oil breaker.

3. It is questionable if insulation integrity even for 12,000-volt designs can be secured with an air breaker comparable to an oil breaker. The design shown in Fig. 7 of Mr. Wilcox's paper will stand 150,000 volts test. The same test on an air breaker would seem very difficult to secure.

4. I should like to ask Mr. McNairy if he considers the form of the current wave shown in Fig. 7 to be quite desirable. There seems to be considerable distortion on the last part of the half cycle. This is probably due to the enormous rate at which energy is expended in the arc. The statement is made that "energy is liberated in the chute at a maximum rate of 200,000 kw." when opening a short circuit of 30,000 amperes at 14,000 volts or 420,000 arc kv-a. This seems to be a very large rate for arc energy made necessary by the inherent limitations of an air breaker.

A device which would open the circuit after having pulled a low-resistance arc would, of course, reduce arc energy and incidentally would not distort the current wave form with consequently beneficial effects upon induced voltages.

5. Mr. Antoniono raised a question regarding the use of solid moving contact terminals of the high-speed d-c. breaker. Four years ago that was quite a new construction and naturally many of our older people questioned it the same as Mr. Antoniono has. It had to run the gauntlet of a great many tests, and after proving itself rather more satisfactory than average, it was accepted. It was new and would not have been accepted unless it was quite satisfactory. It has advantages in that it allows an exceedingly small moving contact to get high-speed operation.

**L. R. Ludwig:** Mr. Brown's paper brings to light an interesting trend in railway electrical engineering. Prior art has given us railway systems which, in addition to the major portions such as motors, require a good deal of auxiliary apparatus for protective and other purposes. Furthermore, protective apparatus has been required at many points within the system and on rolling stock itself. The concentration of this protective apparatus and the consequent elimination of part of it, in so far as this elimination is compatible with operating security, is a big step toward making electric operation economically comparable to that of steam, and so gaining the flexibility which electrical operation provides. It seems, therefore, that too much admiration cannot be shown for the combination of equipment which makes possible removing breakers, their mass and menace, from locomotives and cars.

One feature of the operation with pantograph-lowering relays which may be worthy of discussion, is the high-impedance transformer fault. That is, a fault to ground of a few turns of the transformer may not cause sufficient current to flow in the contact line to operate the substation breakers. The fault would probably grow more serious, and ultimately burn itself to ground at such a point in the transformer that the substation breakers would operate. This would entail additional destruction, however, and it seems that some measure of protection has been lost. It is almost obvious that the additional risk is cheaper than the eliminated breakers; nevertheless, it would be desirable to inquire if the last increment of protection cannot be gained without using the breakers. It is particularly necessary to protect the locomotives as completely as possible.

Two means of gaining this protection to high-impedance faults on the locomotives are self-evident. The first is the use of a small breaker on the locomotive, with proper relaying so that this breaker would operate only in case of a high-impedance fault. The second is a means of deliberately short circuiting the contact line if a high-impedance fault occurs in the transformer, and so forcing early operation of the substation breakers. Differential relay protection would give a full measure of protection to the transformer primaries, but only a partial protection of the secondaries could be secured. Further, the first method would require a breaker, and the second would possibly meet with some objection to short circuiting the contact line.

A striking means of gaining full protection presents itself as an academic possibility at least, if a protective system such as described in the paper "Superimposed High-Frequency Currents for Circuit Breaker Control" were used. It would mean actuating the substation breakers by connecting the contact line to ground through a condenser in case of a high-impedance fault, thus short circuiting the high-frequency system, but not the main power system. Also, full protection of both primary and secondary could be gained by using the differential of primary and secondary high-frequency voltage for relay operation.

**Chester Lichtenberg:** These papers give the impression that high-speed circuit breakers are new. They are not. They have been in service on electrified steam railroads for over 15 years.

There are two classes of high-speed circuit breaker. One has a mechanical latch for holding the contacts closed. The other has a magnetic device for holding the contacts closed. They should not be confused. A high-speed breaker will operate equally well when either means of holding its contacts closed is used. The type of contact-holding mechanism must be chosen for the particular application.

In some cases the high-speed circuit breaker has been condemned because when opened it may cause flashover of a d-c. machine. In such cases it is probable that the position of the breaker has been incorrectly chosen. It has probably been placed on the positive side of the machine. It has not been shunted with resistance. As a result, the current has been abruptly reduced from a high value to zero. So flashover has occurred.

Placing a shunt resistance across the high-speed breaker will not prevent the flashover of a machine if the combination is in the positive lead. If, however, the combination is inserted between the negative brush ring and the commutating or compound-pole windings, short circuit from flashover is prevented. The high-speed breaker on opening abruptly prevents the current's rising further. The arc drawn in the chute inserts resistance in the circuit. The current is quickly reduced to a relatively low value as set by the fixed resistor shunted across its contacts. Then another circuit breaker opens clearing the circuit. The resistance prevents an abrupt circuit clearing. It limits the resultant voltage rise to a relatively small value, too small to start arc-over. Being in the negative side the opening of the high-speed breaker would open any circuit through a flashover. For the flashover, if it occurs, takes place between positive brushes and ground *through the negative brushes!*

**J. T. Hamilton:** (communicated after adjournment) We operate multiple-unit cars having pantograph-lowering relays of the Westinghouse Electric & Manufacturing Company, 371-S2 and U.C.-8 types.

We have found that these relays protect the high-tension transformer windings but do not offer much protection for the low-tension windings of the main transformer, if this short circuits. In some cases where this short circuit has not been sufficient to operate the anchor-bridge circuit breakers, it results in the transformer being totally destroyed due to the overload being sustained.

Where one-car trains are operated, it may be necessary for the motorman or engineer to have access to the pantograph-lowering relay so that it can be reset. This is the practise followed on this property, our motormen being instructed that the relay in question can be reset if no damage is visible on the transformer of the car. We have found that the pantograph-lowering relay has operated sometimes without proper cause. As noted in Mr. Brown's paper, this may be due to the design of the relay in question.

On a-c.—d-c. equipment operating on a zone with d-c. overhead construction, it may be desirable to have a means of disconnecting the pantograph circuit from the main transformer, thereby preventing the d-c. from passing through the a-c. pantograph (if it should be raised accidentally) and then through the transformer with the resultant damage. This is easily taken care of by suitable a-c. circuit breakers.

**C. L. Doub:** (communicated after adjournment) From the standpoint of connection with the Illinois Central Railroad electrification in the layout of this distribution system and in the design, construction, and initial operation of the tie stations, I wish to amplify several points of the paper by Messrs. Monroe and Allen.

The large number of breaker openings during the early operating period has at times been referred to as "hair-trigger" action and cited as a fault of the high-speed breaker. It is significant that after this initial period the number of breaker openings reduced to a normal value (and in fact on some days there have been no breaker openings whatever), though changes have not been in the tripping circuits of the breakers. In the system there are 34 feeder sections which are fed by a total of 70 high-speed substation and tie-station breakers. It is therefore very well established that the so-called excessive number of openings was due to conditions other than the circuit breakers. Although making it difficult to locate the cause of the openings the breakers undoubtedly prevented a great deal of minor burning of car equipment and flashing of converters, and in all probability saved some cases of major damage. These excessive openings did not cause train delays, since breakers were immediately reclosed by substation operators or by supervisory control. On the other hand, they may have saved train delays, through preventing damage of equipment.

The several serious train delays charged to the breakers were due to defects in reset mechanism rather than in tripping, on account of which it was difficult to pick up a large legitimate load of rather steep wave front. The change in reset mechanism has entirely eliminated this fault.

Failure of selectivity occurred practically in no case excepting where two short parallel sections fed stub from a substation and were tied together by tie-station breakers. In this case selectivity is required between a tie-station and a substation breaker carrying the same current, with the same wave front, the only difference in the breakers being in excitation of holding coils from the line and from a battery, respectively. Even under such a severe requirement, selectivity is actually obtained except when the short circuit is remote from the tie station. In such a case the tie-station breaker holding coil receives too small a drop in voltage to make enough difference in speed of operation, since both breakers inherently have high speed. Other cases that have been considered possible failures of selectivity were in all probability due to bridging of section breaks by pantographs at the time of the transient, thereby actually imposing the fault on two or more feeder sections. The probability of this bridging is not at all remote in view of the large number of overlapping sections at interlocking plants and the considerable number of pantographs that are moving at one time.

Another outstanding feature is the great reliance on the high-speed breakers, which is unparalleled in any other similar heavy-duty apparatus. In spite of the large number of breaker openings no case was found where maintenance required more than light dressing of the contacts at periods of six months or more. At several times extensive tests were made involving 25 or more direct short circuits adjacent to circuit breakers within a short time and it was not even considered necessary to inspect contacts after such tests.

The simplicity of auxiliaries and circuits can well be emphasized. No relays or circuits external to the breaker are required for tripping. On this system the only relays are for reclosing and for supervisory control. Although the breaker itself is more intricate than the ordinary breaker, it is sufficiently strong and reliable to cause no difficulty in maintenance.

Practically all of the disadvantages of the breaker on this system have been eliminated or overcome. One disadvantage which cannot readily be eliminated is the difficulty of calibrating the breaker in the field, since currents of actual tripping value are necessary. Thus far there have been no differences in calibration demanding such field work, and perhaps the method supplied for correction for contact wear will prove sufficiently accurate for practical purposes.

On the whole, the disadvantages of the high-speed breaker in this installation have been so far overshadowed by the advantages that they need be given little weight.

**D. C. West:** (communicated after adjournment) In any sectionalized d-c. railway network such as that described by Messrs. Monroe and Allen, the feeder equipment must include two rather distinct operating features if a high standard of service is to be maintained. First, it must be selective between parallel feeder sections, so that only one section is isolated in case of fault. Second, it must provide positive discrimination between legitimate loads and faults. Since the latter of these two requirements has proved to be the more difficult, a brief statement of the problem, and of what has been accomplished in its solution, should be of interest.

The business of an electrified railway is to operate trains, and the electrical equipment is but a means to this end. It is essential that the feeder equipment protect the *service* as well as the distribution system, and it is with this in mind that the manufacturers have attacked the problem. Railway men are quite in agreement that the ideal feeder breaker would be one which would remain closed on any legitimate load to which it might be subjected under either normal or abnormal traffic conditions, and yet would trip out on any fault which might occur on the feeder section to which it is connected. The range of discrimination necessary to accomplish this will vary with the class of service and the type of distribution system, and for different traffic densities within a given system. In a very few cases the minimum short-circuit current will be of magnitude sufficiently greater than the maximum legitimate load peak to permit the use of an ordinary overload device. Usually, however, it will be found that the possible legitimate load considerably exceeds in magnitude the value of short-circuit current incident to a fault at the most remote point on the feeder section. In such cases discrimination is possible only through the use of some form of impulse tripping.

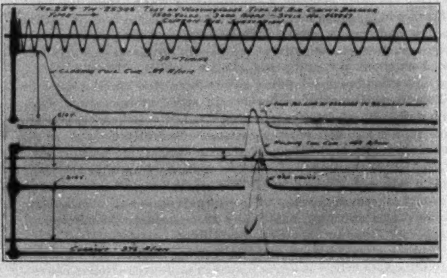

FIG. 7

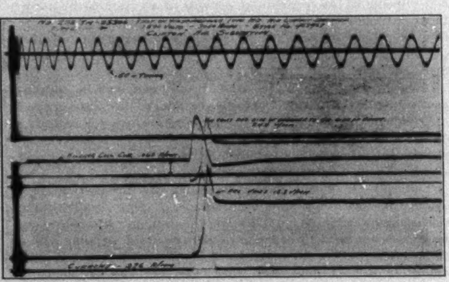

FIG. 8

It is fundamental that a legitimate overload on a railway feeder is the result of a traffic congestion. Railway men will readily appreciate the fact that it is at such times that it is most important to stick to the load up to the very limit of the current-carrying capacity of the feeder circuit. In other words, a legitimately overloaded railway feeder becomes a preference circuit which must remain closed, as long as the circuit is not at fault, in order to clear up the congestion. To open the breaker under such conditions, due to the magnitude of legitimate load, only makes matters worse and presents the possibility of serious delays to traffic. In considering the range of discrimination necessary, then, the maximum legitimate load will be that required to handle such traffic congestions as may occur on the particular feeder in question.

As has been brought out by the authors, the d-c. high-speed breaker, when equipped with an inductive shunt, has a combined overload and impulse tripping characteristic, and is therefore inherently capable of a certain degree of discrimination. Its possible inherent range of discrimination is determined within limits, by degree to which the overload feature can be minimized and the impulse feature can be magnified. The Commonwealth Edison Company, in collaboration with the Westinghouse Electric and Manufacturing Company, recently made a very comprehensive series of tests, at Chicago, on high-speed breakers for supplying power to the feeders of the Chicago Rapid Transit Company. It was demonstrated that the inherent range of discrimination was quite sufficient for the type and proportion of feeder sections comprising probably the major portion of the Rapid Transit system. The relatively high range on these breakers is made possible by raising the steady-current tripping characteristic to such a high value that it is well above the possible peak value of legitimate load swings, even under heavy traffic concentration. The breaker is therefore responsive principally to rate of rise and is affected to a relatively small degree by the magnitude of current flowing in the circuit. For example, with the breaker adjusted to a point well under the setting necessary to trip out on the 6500-ampere current increment due to a short circuit at the most remote point on one of the longer feeder sections, the steady-current tripping value is well above 15,000 amperes. The 8-car Rapid Transit trains require an accelerating current of about 2500 to 3000 amperes, and an oscillograph test on a 6-car train of the Chicago, North Shore and Milwaukee showed a maximum of 5250 amperes during acceleration. The actual discrimination obtained depends principally on the difference between the characteristic of the maximum single increment of load current, and that of the most remote short circuit. As is usually the case, the maximum load increment proved to be that due to the first point of control on the heaviest train. The 6-car North Shore train showed a single increment of 2670 amperes at about 8.4 millihenrys inductance. The inductance in the circuit of the 6500-ampere fault previously referred to, was about 3 millihenrys. It will be possible to handle a concentration of several trains on this section, and still isolate the most remote fault.

On most railway systems, and particularly in the case of steam-road electrification, even this relatively wide range will be found insufficient to provide positive discrimination throughout the system. By the use of properly designed relays energized from impulse transformers in the feeder circuits, it has been found possible to provide a range of discrimination sufficient to cover even the most difficult conditions encountered in service on the various types of systems. The most extreme example is probably that of the Staten Island Electrification of the B. & O. Railway, at New York, which was placed in service in 1925. Here, the high inductance of the heavy third rail made the problem particularly difficult. A feeder equipment was set to trip on a fault applied at the most remote point on the longest feeder section, and the oscillograph showed a current of 1950 amperes at the time the breaker opened. Then, with the same setting, an 8-car train, representing maximum future service, was accelerated immediately in front of the station. The breaker remained closed, although the oscillograph showed a single increment, on the first point of the train control, of 2350 amperes with a rate of rise of about four times that of the short circuit. The maximum accelerating current was 4350 amperes. Since the tripping is in no way responsive to the magnitude of current flowing in the circuit it can handle any number of such trains in a traffic congestion, up to the heating limit of the circuit, as determined by a thermostat on the outgoing feeder copper.

The system is double-track and completely sectionalized, including a tie station. Selectivity between parallel feeders is, of course, necessary and is readily accomplished by means of the same relays.

This case is cited as an illustration of what it is possible to accomplish by the use of devices designed solely for the purpose of obtaining the proper tripping characteristics. It would obviously be impossible to obtain this range of discrimination by using only the *inherent* characteristic of a device such as the high-speed breaker, in which the tripping is responsive only to the magnitude and rate of change of current. However, it is entirely possible to apply such relays to *any* type of breaker, and thus obtain the characteristic required for the particular conditions to be met. For example, it is entirely possible, through the use of relays, positively to isolate faults at all points on the feeder sections in the district between Brookdale and Harvey Substations, without the addition of any tie stations, and still permit the handling of larger trains and considerably heavier traffic.

**H. C. Graves:** (communicated after adjournment) Mr. McNairy has divided the time of operation of the high-speed circuit breakers into three parts as follows:

1. Time required for relay operation.
2. Time required for the separation of contacts.
3. Time required for extinguishing the arc.

He also mentions that by using breakers, as he has described, the time of relay operation can be eliminated.

To compare the speed of the breaker that uses relays, with those described by Mr. McNairy, it would be necessary that the time required for relay operation should also include the time necessary for the building up of the tripping current. Thus, if Item 1 should read: "The time required for relay operation and the building up of the tripping current," Items 2 and 3 could then be comparable on the different breakers.

Fig. 4 in his paper brings out the fact that the building up of the tripping current lags behind the building up of the line current. Assuming this wave in Fig. 4A to be a 25-cycle wave, the current rises to a maximum in 0.01 seconds, but the tripping current in Fig. 4B does not rise to a maximum until 0.016 seconds.

Also the tripping-coil current does not rise rapidly as does the line current, but rises gradually at first, and more rapidly later. This time lag is equivalent to something over ⅙ cycle, and relays suitable for this application are much faster than this. Oscillographs show that the trip-coil current builds up to a tripping value with practically no time delay after relay contacts close. Thus the building up of the trip current in the breaker as described by Mr. McNairy, is no faster, if as fast, as that described by Mr. Wilcox.

One important condition which must be met by the protective equipment on a system of this type can be described as follows: With a load adjacent to a station bus on a contact line, a secondary current of 5 amperes may flow away from the bus to the load. In Fig. 13, this current appears in the trip coil and the return path is not only through the saturating resistor but also through three other trip-coil circuits in parallel with the saturating resistor. The trip setting must be adjusted so as not to trip under these and other conditions such as the magnetizing of train transformer banks after the contact line has been disconnected, bus short circuits, etc.

After a train load has been connected until the fluctuations in the trip circuit have died out, a current increase of more than five amperes or more than ten amperes total fault current must flow to cause tripping. It is quite conceivable that this condition cannot always be met in practise.

Our objection to the scheme of connections as shown in Fig. 13 is that a change in the number of feeders connected changes the calibration of the other tripping circuits. The greater the percentage of change, the greater the effect.

If the breakers are so set that the above conditions will not cause faulty tripping of the breaker, then a comparatively large unbalance in line current must occur before the breaker will trip. If the breaker can be set so as to operate correctly under all conditions, it cannot be set so as to avoid a considerable amount of sequential operation. That is, the breaker at one end will open first and then the breaker at the opposite end will open. This is a bad condition from a standpoint of interference in signal and communication circuit, since the fault current is high and the distance of the exposure is possibly the entire distance between stations.

In Fig. 13 is shown the relay protection, including back-up relays, for a typical application. The back-up relay is shown as an impedance relay. This should prove to be a satisfactory form of protection in that it, alone, if of the induction type, should afford proper selectivity even if no other form of protection were included. However, here again simultaneous tripping of breakers at both ends of a faulty section would not take place and some time delay would be necessary.

**H. M. Trueblood:** (communicated after adjournment) I should like to add briefly to the discussion touching the relative inductive effects of single-phase railways and power circuits.

Aside from the other factors mentioned by Mr. McNairy, and by Mr. Hanker in his discussion of Mr. McNairy's paper, a comparison between the two systems should not, I think, overlook the greater probability, for short circuits on railway circuits, that faults will be of low or negligible resistance. Also, with multi-track roads, the inductive effects of current in the trolley-track loop may be of considerable importance in cases of closely exposed circuits, such as railway communication circuits carried on poles located on the right-of-way. Again, if a 60-cycle power line is provided with a ground wire or wires, such conductors carry a part of the return fault current, acting in this respect like the rails in the railroad case. Although they are not so effective in this function as the rails, they may carry substantial amounts of return current, especially if they are of high conductance. Mr. Hanker refers to the relatively small amount of induction in railway sections not adjacent to the fault. The significance of this, in a comparison of the two systems, depends upon the character of the exposure. While this factor is undoubtedly important so far as long, close parallels are concerned, it would be of minor weight from the standpoint of a type of exposure frequently met with, unless, in the railway case and not in the other, there is adaptation of substation location to the exposure conditions.

In Mr. Hanker's discussion, the statement that for equal fault currents the induced voltages for the 60-cycle system would be about ten times as great as for the 25-cycle railway system, is apparently based on 75 per cent rail current in the latter case. While this is a figure customarily used for four-track roads, it does not hold for a smaller number of tracks. With a single-track road, for example, the factor of ten mentioned by Mr. Hanker would be reduced to five or less. Either of these factors would, of course, be much larger than the ratio of actual induced voltages. In fact, as is suggested by Mr. Hanker's numerical example, fault currents on 25-cycle railways are ordinarily several times greater than on 60-cycle power systems, in cases where line impedance is an important factor, as it usually is where parallels are long enough to produce the higher values of induction.

A general comparison of the kind under discussion is difficult. To get numerical results, certain factors, such as line voltage, connected capacities, fault resistance, etc., must be fixed. For equal line-to-ground voltages, I believe it to be true that a three-phase 60-cycle system with dead-grounded neutral, when short-circuited to ground through zero impedance, would usually induce larger voltages than a single-phase 25-cycle railroad similarly short-circuited, provided exposure conditions are the same and such as to make the inductive effect of the current in the trolley-track loop negligible. This preponderance of the induction from the 60-cycle system tends to decrease with increasing length of exposure.

**J. W. McNairy:** The discussion by Mr. Graves, supplementing the paper by Mr. Wilcox, brings up many interesting points in connection with the selective operation of high-speed a-c. breakers applied to a network, particularly in connection with high-speed impedance relays.

The impedance of a given circuit may be easily determined from effective values of current and voltage under sustained conditions and used to actuate standard impedance relays. However, high-speed operation approaching that of other methods necessitates the determination of impedance by the current and voltage conditions existing for a small fraction of a cycle immediately following a short circuit under all possible transient conditions and presents a more difficult problem.

With low-power-factor circuits the ratio of instantaneous current to voltage varies for every point of the current wave. A relay utilizing the difference in torque between a potential restraining element and a current operating element receives a maximum operating torque on a low-power-factor short circuit near the zero point of the voltage wave where the current is a maximum. The restraining torque near zero of the voltage is necessarily relatively slight. At zero power factor there is, of course, no restraining voltage at the instant of maximum current.

It is entirely feasible to design over-current relays capable of closing contacts or mechanisms capable of unlatching in approximately 0.001 sec. after the trip point is reached. The design of an impedance device for such a speed of operation, however, is impractical because of the response to instantaneous current values and operation at the peak of the current wave where the voltage element has little or no effect.

It therefore appears essential that the speed of operation of an impedance device be limited so that the operating forces are dependent upon the effective values of both the current and voltage for at least a considerable portion of a cycle.

Further, where such a device is used, it should be noted that for a given applied voltage and a given external circuit both the instantaneous and effective values of the initial short-circuit current may vary over a considerable range. This variation results from the displacement of the short-circuit current wave and is dependent upon the instantaneous voltage at the time a short circuit occurs only and not on circuit conditions. With a completely displaced current wave the peak occurs one-half cycle after the incident of short circuit, at which time the voltage is approximately zero. The maximum current is twice that of a symmetrical current circuit, conditions being the same. High-speed impedance relays must, therefore, be set sufficiently high so that displaced exchange currents over unfaulted feeders will not operate these relays. The length of feeder which can be protected under short-circuit condition on a system of the type specified, with a symmetrical short-circuit current, is consequently limited. As a result, symmetrical short circuits at a considerable distance from a substation are likely to result in sequential operation of the two breakers at the ends of the faulty feeder.

It would appear, in view of the above, that a selective system based on the accurate determination of impedance from current and voltage conditions existing for a fraction of a cycle presents many new problems not associated with the usual type of impedance relay operating at slow speed.

In this connection, an accurate impedance device capable of operating in a half cycle must be equipped with a potential element which can respond to an instantaneous reduction in voltage, such as occurs at the instant of short circuit. The application of a short circuit in front of a station, at the instant the voltage is near the peak of the wave, requires that the current through the voltage restraining element of the relays at adjacent stations be reduced to a fraction of that existing prior to the short circuit in a very short period of time if true impedance is the basis of operation.

A further point is of interest in connection with the application of impedance relays to a system of the type which has been repeatedly discussed. The heavy current resulting from a short circuit at or near one substation greatly reduces the voltage of the high-tension line feeding adjacent substations. Impedance relays so designed that they will not operate with an exchange current of 2700 amperes over unfaulted feeders, with greatly reduced voltage, inherently require a relatively large current under load conditions where the restraining voltage is not appreciably reduced. This point is of very considerable importance in connection with any system where all substations are fed from the same source of power.

Sequential operation of circuit breaker at the two ends of faulty feeder, with short circuit near one station, is, of course, detrimental only when it results in a longer duration of the current over the feeder. When operating devices, such as impedance relays, receive an impulse only just sufficient to operate the resultant unbalanced torque between operating and restraining element which is relatively slight, full speed operation of the relay is difficult to obtain. Under such conditions the total duration of the short-circuit current over the feeder may not necessarily be shorter than that obtained by devices which do not initiate the operation until the second half cycle of the short-circuit current. This is particularly true where a considerable portion of a half cycle is required before release of the relay mechanism.

Referring to Mr. Hanker's discussion, there seems to be some misunderstanding as to the characteristics of a saturated current type of tripping circuit applied to the breakers described in the paper. The impulse voltage generated by the saturated current transformers is not a function of the total current through the corresponding breaker, but is a function of the current applied suddenly under short-circuit conditions.

If, therefore, the breaker supplying a faulty feeder is carrying a load of 1200 amperes and a short circuit occurs, resulting in an additional 2700 amperes in this feeder as well as three paralleling feeders, the initial current of 1200 amperes has practically no effect on the tripping circuit of a breaker connected to a faulty feeder. The voltage generated by this tripping circuit is proportional to the 2700 amperes increase resulting from the short circuit and is equal in the tripping circuits of all feeder breakers carrying the same increase. The only return path for the tripping current is through the saturating resistor common to all breakers, the resistance being sufficiently high to limit the current below the tripping point of the breakers.

By changing the value of the saturating resistor the ratio of the tripping point with a simultaneous current increase to the tripping point with a current increase through one feeder only can be made as great as desired. The trip point for a simultaneous current increase through all breakers can be made infinitely large by open-circuiting the saturating resistor.

It should be pointed out that the setting of the current-transformer trip is not determined by steady load requirements of the feeder. The limiting condition is the maximum increase in load which can take place instantaneously on the feeder. It is entirely feasible to have a breaker of this type set to trip with a current increase of 600 amperes, at the same time carrying a steady overload of any desired value without tripping. Due particularly to starting currents resulting when transformers of locomotives or cars are suddenly energized, it seems desirable that any protective system be capable of picking up such transformers regardless of the steady load conditions. The saturated transformer trip has the proper inherent characteristic. The effect of the pre-setting arrangement described by Mr. Graves results in a similar characteristic.

The selective operation of the differential circuit described in the paper is not dependent upon accurate setting of the breakers.

Fig. 4 of the paper was plotted to show conditions with a symmetrical short circuit because this is a limiting case in which the minimum tripping current results. The flat section of the tripping-current curve shown occurs only after the first tripping impulse has been supplied by the tripping transformers. In no case does a flat section precede the first tripping impulse. The calculations can be easily made to show the performance of the transformers with completely displaced wave by introducing a transient term in the equation for the line current. Numerous test records indicate that the tripping arrangement is, if anything, more effective when the current wave is displaced.

It should be pointed out that the exchange current betweent stations over the 11-kv. feeders results from the impedance drop in the 132,000-volt line between two substations and the step-down transformers supplying the short circuit directly. An exchange current of 2700 amperes results only with maximum generator and high-tension line capacity. A short circuit directly in front of one station reduces the voltage of the high-tension line to a relatively low value. If the drop through the low-reactance transformer and high-tension lines is sufficient to result in 2700 amperes exchange current per feeder between stations, or a total of 9800 amperes for four feeders, on the initial short circuit directly adjacent to one station, a very considerable increase in current will be realized as soon as the heavy short circuit is removed from the high-tension line, this current being effective in tripping the remaining breaker at high speed.

Mr. Hanker evidently interpreted my statement to the effect that the desired form of high-speed breaker is one which stops the current at the first zero after the first full half cycle to mean one-cycle operation. This is not the case, however, as a short circuit involving the time of a full half cycle rarely occurs under short-circuit conditions with the breaker described. A great percentage of test records taken on breakers of the type described in the original paper shows a single loop of current, a few show two loops, the duration of which in practically all cases is considerably less than one cycle.

Regarding the question of insulation of the air type breaker, I should like to know whether or not Mr. MacNeill feels that the 12,000-volt circuit is ordinarily subjected to voltages of the order of 100,000, or whether he feels the failures are due to local operating conditions, such as dirt, smoke, etc.

There are a great many pieces of apparatus connected to a 12,000-volt railway system which are not capable of standing 100,000 volts. There is nothing inherent in the design of the air breaker to limit the insulation for any reasonable requirement on 12-kv. systems. We feel that the type of insulation which is being used for the air breaker is particularly suited for the mechanical shocks of high-speed operation.

Another question raised was whether or not high voltages were likely to result from too rapid decrease of the current such as shown by Fig. 10. The particular figure referred to by Mr. MacNeill had plotted on it the voltage taken from the oscillogram. The voltage was 10,000 volts. Voltages have been checked by other recognized methods and I can say quite frankly that direct comparisons have shown less tendency to high voltage with the air breaker than with the oil types.

There has been no record published covering the liberation of energy in the oil breaker at rupturing currents near its interrupting ratings. It is my impression that with the heavy currents of 30,000 or 40,000 amperes there are a great many effects that come into operation of the circuit breakers, other than the magnetic blow-out effects, tending to cause high voltage. We know there are certain types of oil breaker which depend largely on explosion effects for opening the circuit.

I have an impression that any type of oil breaker, by virtue of those explosion effects, is quite likely to decrease the current more rapidly than a breaker where there is not available oil to furnish gas pressure for explosion. Some of this effect is present in an air breaker but we find from the experimental work we have carried on that the difference in this effect between the lighter and heavier currents is not nearly so pronounced as in the oil breaker.

Mr. A. C. Graves, Jr. has brought up some additional points in his discussion submitted after adjournment that require further consideration.

The statement was made that the tripping current as shown by Fig. 4A of the original paper does not reach maximum until 0.016 sec. after the beginning of the short circuit. It might be inferred that under any short-circuit conditions the breaker in question would not receive tripping current until the peak of this current is reached. Such a statement applies, however, only where the breaker is operating with current just sufficient to trip. Where a short circuit of any considerable magnitude is involved the trip point of the breaker is reached considerably in advance of the peak of the trip current and the breaker receives its tripping impulse in sufficient time to limit the current to a single loop in a majority of cases. The case taken for Fig. 4 is the limiting case where the current is just sufficient for operating the breaker.

As pointed out in an earlier discussion of Mr. Grave's description of impedance relay, it is difficult to see how an impedance relay can be constructed to operate on true impedance in a fraction of a half cycle, taking into account all possible transient conditions.

After all, an impedance relay receives its operating torque from the line current, this current usually reaching a maximum between one-quarter and a half cycle after the beginning of the short circuit. With the low power factor existing in short-circuit conditions, the voltage is a minimum, and, therefore, there is a pronounced tendency for the impedance relay to operate at this point of the short-circuit current wave unless a considerable time lag is introduced. While it is entirely possible to build relays which will close the tripping coil circuit in a very short time after the trip point is reached, such relays are usually not of the impedance type.

It is again pointed out that the setting of the saturated-transformer type of tripping circuit is not limited by steady load conditions. It is only necessary to set the circuit breakers so that the maximum load increase encountered in normal service will not operate when occurring on a single feeder. The limiting condition quite likely is that resulting from starting currents when energizing transformers, and any high-speed protective system which will operate in a fraction of a cycle must have sufficient leeway to prevent operation when transformers are energized at a time when the feeder is loaded near the maximum. The load pre-setting arrangement described by Mr. Graves in his original discussion of Mr. Wilcox's paper apparently permits a sudden application of load above the steady load being carried by the feeder in much the same manner as the saturated-current-transformer type.

One further point in connection with this application is that it has been repeatedly pointed out that under certain conditions on a given system the fault current over unfaulted lines between substations may reach 2700 amperes. This means that an impedance relay used for protection must be set so that 2700 amperes over the unfaulted feeder will not result in breaker operation, taking into account the fact that a short circuit at or near one substation reduces the voltage of the common high-tension system at adjacent substations to relatively small value. It is difficult to see how a relay can be made to trip at a load of 1200 amperes when the voltage is not appreciably reduced and still remain closed with an exchange current during short circuit of 2700 amperes between substations with the restraining voltage considerably reduced.

**W. P. Monroe:** Mr. McNairy asked two questions regarding our statement as to the inaccuracies of the calibrating mechanism.

We referred in our paper to the means of calibration which is obtained by a set screw which turns in and out of the holding-coil core and the marking of the calibration scale on a plate parallel to this screw. The scale is small but covers a considerable range. I believe it is obvious that with such a scheme of adjustment a high degree of accuracy would be difficult. He asked if this disadvantage has affected our operation. Since we have been in operation only two years and our initial adjustments are still largely in effect we believe our experience is not sufficient to enable us to know whether this will be a serious handicap. We anticipate that the wearing of the contacts of the breaker will affect the calibration somewhat.

In regard to holding in the circuit breaker on overloads, this can be done, as Mr. McNairy says, by remote control with a push-button, changing the calibration temporarily, but we were referring only to our own installation. In our unattended tie stations such a feature would entail undesirable additional supervisory control circuits.

In regard to high-voltage surges, without going into the theory of surges resulting from high-speed breaker operation on short circuits, I would say we mentioned this objection because it had been mentioned to us and we wanted to publish the fact that we had noticed no disadvantage of such effects, whether they exist in alarming proportions or not.

# Formula for Minimum Horizontal Spacing of Transmission Line Conductors as Affected by Danger of Contact in the Span

BY PERCY H. THOMAS[1]
Fellow, A. I. E. E.

THE present contribution is for the purpose of deriving a logical formula to be used as a guide in the determination of the minimum safe horizontal spacing of transmission line conductors, and is offered for discussion. By minimum safe horizontal spacing is meant the least spacing that will insure safety against short circuits between conductors due to their swinging together out in the span under the influence of wind or ice, and has no relation to the separation of conductors transversely at the towers, as required for securing the necessary clearance to the tower structure. The latter separation is usually controlling, but a number of cases occurs where the getting together in the span requires a wider spacing, such, for example, as long spans, or two circuit horizontal arrangements of conductors.

### THEORETICAL ANALYSIS

A study of these questions shows many erratic factors bearing on the danger of contact in the span between cables *horizontally* spaced, so that apparently experience data rather than mathematical calculation must be the final dominating consideration. However, these experience data are exceedingly scanty and difficult to interpret, so that a theoretical analysis is likely to be of real value.

### STEADY UNIFORM STATE

Considering a transverse wind, uniform in direction and steady in strength, we have a very simple case, for all the cables will be deflected in the same direction and by the same amounts, and will maintain exactly the same horizontal separation regardless of the direction and strength of the wind, even if the wind be straight up. Even if the wind blows at an angle with the direction of the line, the same condition exists. This is a very important conclusion.

An examination of the relations involved shows that with a strong cross-wind blowing the dropping of the ice on one cable leaving another cable in the same span coated would not have much effect on the relative side-swing of the two conductors in the case of aluminium cable steel reinforced, since the weight drops with the ice removed more or less in the same proportion as the wind surface is reduced. A special study should be made in each case for copper cable, where the balance is not so close. This action of steady state side-swing giving unequal displacements from ice unbalance is governed by entirely different conditions from the general case and is not hereinafter considered.

### NON-UNIFORM WIND CONDITION

When the wind is irregular in time or direction, or uneven at different points, there will be more or less tendency for the cable to depart from the true catenary curve and the possibility of contact occurs. Obviously, it is the transverse horizontal components of the deflection that tend to cause contact, not the vertical. With a strong wind blowing across the line, say 60 mi. an hour, air moves at a velocity of 88 ft. a second so that a time of perhaps 2/10 sec. elapses between the time when the air impulse acts on one cable and when it reaches the next cable in the same horizontal plane, so that there is no time for actual motion of one cable ahead of the other cable, due to the same high velocity wind impulse. Furthermore, it is exceedingly unlikely that with a *high velocity* transverse wind, there can be any great change of velocity or direction of the air in traversing the short distance between adjacent cables. In fact, the direction of the air must in general be substantially parallel to the ground, as there is no place for air to go elsewhere. This means that all cables in the first approximation are subject to the same transverse air impulses at any one instant of time, substantially. This is the reason, no doubt, that trouble with wires getting together in the span is so rare. Where the surface of the ground is curved or local obstructions exist close to the line, eddies will of course be produced. This is a vitally important case and will be considered later. The only exception would appear to be a cyclone on a small scale, with an axis inclined to the vertical by a large angle, this being practically beyond any experience of which the author is aware. But there are actual conditions in which cables have got together so that the necessary irregularities must sometime occur.

The most important active factor in preventing contact in the span with transverse winds is, no doubt, the restraining force of the tension in the cable which tends to prevent deformations of the catenary by the wind. In long-span construction, this tension is of very material amount and has a remarkable restraining effect. To deflect a vertically hanging wire carrying a 5000-lb. weight, one degree from the vertical will require a horizontal force of 85 lb. applied at the weight. A wind producing a pressure of 8 lb. per ft. must blow against 10.6 sq. ft. of area to produce such a force.

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Deflection of a cable from the catenary shape, however, will require much more force than the hanging weight, since both ends of the cable are fixed and it is already a convex curve. Therefore, in accordance with the law of increase of tension in a catenary with decrease of sag, which approaches the action of a toggle joint, the straightening out of other parts of the catenary cable, which must accompany bulges in the curve at any point, develop very high counter tension. A careful consideration of this matter will show that a catenary, under wind pressure and with small sag and high tension, is a very stable curve against deflection in the plane of the curve.

Furthermore, the swinging of cables will be largely "dead beat" on the wind (at least with transverse winds), and *will have no material pendulum or oscillatory movement.* It will be remembered that as a theoretic conclusion, pendulum action can occur only as the energy stored in momentum carries the moving body beyond a point of equilibrium against an elastic controlling force, thus paving the way for a return swing caused by the controlling force. The *velocity* of movement of the conductor in an actual span is relatively small, so that the kinetic energy stored in the moving cable cannot be sufficient to move it against gravity more than a few inches. No oscillatory movement of a few inches could be of serious importance in a transmission line. A velocity of one foot per sec. will cause a rise against gravity of only 0.02 ft. A velocity of 8 ft. per sec. would be required for the kinetic energy to be sufficient to raise the cable one foot against gravity. Thus it seems that due to wind across the line, there is little chance of conductors getting together horizontally.

Considering these principles in numerical relations, it may be assumed as an approximation that the danger of the deformation of the catenary and contact between cables is inversely proportional to the cable tension, other things being equal. It may be assumed also that it is directly proportional to the span, for obviously any given proportional deformation will give an actual displacement in feet proportional to the length of the span. Further, the displacing force will be proportional to the diameter of the cable representing the exposed surface.

The tension in any span taken as due to wind and weight will be proportional to the resultant of the wind and weights $w$, acting on the cable times the square of the span divided by the sag closely but not exactly.

The danger of contact would then be proportional so far as the above factors are concerned to

$$\text{Span} \cdot \frac{\text{Sag} \cdot \text{Diam.}}{w \cdot \text{Span}^2} = \text{Sag in per cent} \cdot \frac{\text{Diam.}}{w}$$

and might be written for preliminary purposes as

$$\text{horizontal spacing} = C \frac{\text{Diam.}}{w} \cdot \text{Sag in per cent where}$$

$C$ is a constant.

The effect of cable weight is to give greater tension and hence is favorable; but its effect is already included in the formula. The effect of diameter would seem to be relatively unimportant because both the force restraining (tension) and the force causing deformation (wind puffs) are affected more or less alike by diameter. This mathematical expression will be further considered below.

Longitudinal wind will cause a deformation of the catenary in a vertical plane but so long as it is a horizontal wind it will not tend to cause contact.

The vertical component of any wind, whether transverse or longitudinal, tends to support the weight of the cable and thus reduce the tension which, in turn, tends to render contact in the span more likely and this is probably the principal cause of such trouble. If the uplift is sufficient to take all the weight off the wire, there is tension due only to transverse components of the wind. Under such conditions, minor forces will be largely free to move the conductor about in an accidental manner, rendering contact much more likely. For example, a gusty longitudinal wind blowing under a line up a concave, rising hillside, would be very favorable for trouble, for the wind would have an upward component which would take off the weight and tension on the wires and the irregular transverse components would be free to bring them together.

A 6.5-lb. per sq. ft. upward wind component will take all the weight off a No. 4 copper cable and a 15-lb. wind all the weight off a No. 0000 copper cable.

For all aluminum cable, the respective corresponding pressures are 2.0-lb. wind and 6.2-lb. wind, and for aluminum cable steel reinforced 2.8-lb. and 6.4-lb. A 2-lb. wind on cylindrical surfaces corresponds to a velocity of 27 mi. per hour actual, and 6-lb. to about 60 mi.

Causes of steady upward components of wind would be configuration of the ground or natural and artificial obstructions, such as trees, buildings, sign boards, gullies, etc. In any particular case, from an examination of the ground, a sufficiently correct inference as to the directions of air currents can no doubt usually be made.

The breaking off of ice and heavy wind in an adjacent span or other causes may produce a pulling of a certain short length of cable from one span into the next, but this will effect danger of contact in the span only indirectly, and whatever conditions might be set up to render the line safe in general against transverse wind conditions in the span would probably protect also against the effect of pulling from one span to another.

Similarly, transverse conductor swinging may be carried from one span to the next, but such swinging is likely to be largely in synchronism for all conductors, unless in cases of very irregular ground configuration.

Apparently relatively short spans and very low stringing tension in the conductor tend to increase danger of contact, especially since it is highly probable that irregular wind and ground conditions do not exist over the whole length of any very long spans. This seems to be confirmed by reports of the behavior of extra long spans.

### SIDE HILL EFFECT

A consideration of side hill effects,—that is, lines located on side hills,—is very interesting. So far as the main wind pressure is concerned, it must follow the slope of the ground, and will have an upward or a downward component affecting gravity. Puffs, or eddies, may occur in other directions. This means a steady uplift conponent or a downward component on the cable, on side hills, decreasing or increasing the effect of weight. This may greatly affect the magnitude and direction of the resultant loading on the cable on steep hill sides.

With copper cable, under a transverse wind, the angle of cable deflection from the vertical with an uphill wind will be somewhat, but not greatly, increased. With aluminum cable, even when steel reinforced, the uplift will sometimes exceed the weight in stiff winds causing a swing above the horizontal. This does not appear, however, to increase the risk of contact between cables, except where erratic variations in the strength of the wind may cause large variations in the vertical plane. The variations in a vertical plane, however, would tend to restrain deformations in the horizontal plane on account of the fixed length of the cable. It is highly probable that except for a very few exposed hill sides there will be a tendency for the wind to have a less velocity on hill sides than in the open. On the other hand certain formations of the terrain have the power, like some tapering river estuaries subject to tides, to cause an increase of velocity by deflections and reflections.

The most important aspect of this uplift by a component of the wind on the cable, however, is the possibility of the uplift raising the cable at the tower up against the under part of crossarm. It is possible that this may account for some unexplained flashovers at towers. A glance at the tables showing dead weight and wind pressures will evidence the importance of this matter for aluminum cable, especially for smaller cables. A dead weight hung on the end of an insulator string may be very useful on certain exposed steep hill sides.

Considering the different effects of various metals, it may be said that plain aluminum is the most dangerous, not because of its light weight so much as on account of its lack of strength and the resultant loose stringing.

As between copper and A. C. S. R., the preference is not so clear—the greater density of copper would be of advantage at least in so far as it gives greater tension, while the greater strength of the A. C. S. R., if used to advantage, leads to a higher cable tension and makes a less percentage sag and gives decidedly the stiffer catenary.

A downhill wind on the side hill will increase the *apparent* weight of the cable, and in the case of A. C. S. R., may more than double it; but this will not greatly increase the resultant stress on the conductor.

### WIND PUFFS AND EDDIES

No definite measure of wind irregularities seems feasible. We know that air in wind motion will act like water at the bottom of the sea, for air is substantially incompressible for variations of atmospheric pressure. Where a current meets an obstruction, it will be deflected to the side, or upward, with an increased pressure, but without increase of velocity. If a current, however, is directed into a funnel shaped cavity or recess, there may be a somewhat increased velocity. Air seems to be subject to cyclonic effects more than water, but they do not seem to be especially destructive to transmission lines. Presumably, the danger from these puffs and eddies is measurable by the factors already discussed above.

The only way to take account of expected irregular variations in wind action in the proposed formula is to make a purely arbitrary alteration in the factor $C$ for any unusual conditions.

The only clear danger of contact in the span arises when, through deflection, by obstacles or a hollow formation of the surface of the ground, there is an upward turn of the wind, tending to raise the wire and thus give it slack within the span for accidental deflections.

Such obstacles and hollow surfaces must lie in direction along the line, so that a considerable length of span may be affected.

A typical example has been reported in a case where a transmission line paralleled the edge of a wood for a certain distance just outside. At this portion, the conductors were blown together in the span a number of times, presumably with the wind toward the wood. The obvious explanation would be the turning up of the wind strata blowing along the ground when they reached the wood, thus tending to raise up the conductors and allowing them to get together through the slack with no strong transverse pull to keep them all to one side.

The conclusion would seem to follow that each line should be gone over when installed for the purpose of locating wind obstructions or hollow shaped earth formation, and special precautions taken to prevent contact of wires wherever need appeared. It would be uneconomical to increase the width of structures over a whole line to meet a few determinable danger spots.

In the rare instances of contact in the span, known trouble has sometimes been due to other conditions than wind, which should be borne in mind. For example, electromagnetic forces due to short-circuit currents have been known to produce contact of wires, presumably caused by reaction due to the sudden cutting off of the short-circuit current, since heavy current of itself tends to separate the wires. However, except in a few extreme cases of heavy wires close together, there is little likelihood of this happening, although an examination of the forces should be made in all close cases. A transverse magnetic force per foot of about 17 per cent of the weight of the conductor would be required to deflect the center of the span 10-deg. from the vertical. This cause of contact is not further considered in this discussion.

Since the same spacing must ordinarily be used throughout the line, the constant $C$ should be determined by comparison with experience and should presumably be taken as applicable to the *normal tangent level span under Class "A"* loading conditions (or any other conditions that might be agreed upon) and it must contain factor of safety or margin enough to cover extra long spans and other variations. The apparent added risk from extra long spans is balanced partly by the much smaller chance of excessive air puffs and eddies on the large scale of the long span.

In choosing an actual formula, certain other considerations may be taken into account.

The jumping distance of the voltage is, of course, a factor to be taken directly.

The effect of the length of the insulator string appears to play little part in any of the above analysis and a long string would not seem to render contact more likely than a short string. Apparently antics in the middle of the span would not be greatly affected by the length of the insulator string. Nevertheless with our present imperfect knowledge of this subject, we would not be warranted in ignoring the length of insulator string. It may reasonably be assumed as an empirical formula that the horizontal spacing should include a part equal to the side deflection of the insulator string to the 30-deg. position. The normal spacing is certainly not likely to be reduced more than this due to the string. For pin type insulators this part becomes zero.

The above formula may then be set up as follows:

$$\text{Horizontal spacing} = C \cdot \text{Sag in per cent} \cdot \frac{\text{Diameter cable}}{\text{Class } A \text{ loading}} + D + \tfrac{1}{2} \cdot \text{Length of insulator string}$$

Where $C$ = A constant chosen arbitrarily for each line to take account of the sort of metal of conductors, wind conditions, character of terrain, etc.

$D$ = Jumping distance of line voltage—one foot for each 110 kv.

Sag in per cent is expressed without decimals, that is, 2 per cent is written "2."

If $C$ be taken as 4 for copper cable and 3.5 for A. C. S. R. and their sags in the normal span respectively as 3.75 per cent and 3.25 per cent the spacings for No. 0000 cable would be as follows:

For 44 kv. Pin Type Insulators

No. 0000 Cu. No. 0000 A. C. S. R.

$$4 \cdot \frac{0.5275 \times 3.75}{0.927} + 0.4 \,, \quad 3.5 \cdot \frac{0.564 \times 3.25}{0.764} + 0.4$$

$$= 9.0 \text{ ft.} \qquad = 8.8 \text{ ft.}$$

For 66-kv. Suspension Insulators

ditto $+ 0.6\, \tfrac{1}{2} \times 2.25 = 10.3$, ditto $+ 0.6 + \tfrac{1}{2} \times 2.25 = 10.1$

For 110-kv.

ditto $+ 1.0 + \tfrac{1}{2} \times 4 = 11.6$, ditto $+ 1.0 + \tfrac{1}{2} \times 4 = 11.4$

For 132-kv.

ditto $+ 1.2 + \tfrac{1}{2} \times 5 = 12.3$, ditto $+ 1.2 + \tfrac{1}{2} \times 5 = 12.1$

For 220-kv.

ditto $+ 2.0 + \tfrac{1}{2} \times 8.0 = 14.6$, ditto $+ 0.2 + \tfrac{1}{2} \times 8 = 14.4$

The above formula is the mathematical equivalent of the following:

In comparing two spans, *the horizontal spacing*, other conditions than those specified being equal,—

Should be twice as great in the first span when both have the same length, but the conductor in the first has one-half the tension of that in the second:

Should be twice as great in the first span when the first is twice as long and both have the same tension:

Should be the same in both when the first is twice as long and the second has half the tension:

Should be twice as great in the first when the diameter of the cable is twice as great,—the sag, span length, and loading per foot being the same in both:

Should be twice as great in the first when the loading is half,—the span length, the sag, and the diameter being the same.

In the formula tension and span length are the critical factors, one being as important as the other. The disadvantage of a long span can be made up by a higher tension and vice versa.

As instances of actual lines where an actual comparison can be made with this formula may be mentioned: (1) The Davis Bridge line of the New England Power Company with a two-circuit line of 12-ft. horizontal spacing on 110-kv. for No. 0000 copper wire; (2) A somewhat similar line of the Appalachian Power Company with 10-ft. spacing for 88 kv. for No. 0 copper conductor.

In conclusion it may be said that as a result of the various considerations already discussed, and of an examination of the proposed formula:

1. The safety against contact in the span depends apparently more upon tension in the cable and configuration of the ground than anything else.
2. The most dangerous conditions are probably those

in which the general wind velocity is not too high, this signifying low conductor tension, and is more or less parallel to the line, so that neither cable is blown far to either side, and in which there is an obstacle causing a local upward turn in the wind. The conditions will be worse in short spans and with small cables and large sags.

3. The cable conditions on side hills deserve much more consideration than they usually get.

4. The advantage of copper over A. C. S. R. or A. C. S. R. over copper, if either can be established, should be taken into account in the arbitrary constant *C*, as should also any variations of the terrain making the general conditions of any one line better or worse than normal.

The author has made considerable effort to locate examples of contact of horizontally spaced cables in actual service, where the conditions are known, for the purpose of selecting a constant for the formula derived above, but very few such cases have been discovered, although some 30 or more of the engineers in this country and Canada, with the best opportunity to know of such experiences, have been consulted. The following letters and extracts describe a few very interesting and pertinent cases and seem definitely to support the conclusions of the paper.

"THE MONTANA POWER COMPANY
Butte, Montana

August 2nd, 1927.

Mr. Percy H. Thomas,
120 Broadway,
New York, N. Y.
Dear Sir:

*Case 1.* We have a 60-mi., 100-kv. line built-on steel towers passing through the north end of the Tobaccoroot Mountains. The line is No. 0 hard drawn seven wire copper 10-ft., 6-in. horizontal spacing, 36-in. insulators strung at 1200 lb. tension at 32 deg. fahr., with 2⅜-in. Siemens Martin ground wires midway between phase wires and four feet above the phase wire plane. Ground wire was strung at 1500 lb. at 32 deg. fahr. This line had several spans ranging from 1000 to 1200 ft. crossing valleys and gulches more or less at right angles to the line, where the wind was apt to be severe and where it no doubt would strike one end of the span more than the other end and where it might have had a vertical component of at least 30 deg. to the horizontal. Many of these spans suffered short circuits during wind storms so that it was necessary to anchor the wires in midspan with hold-down anchors so run as to spread the two outside wires away from the middle wire at mid-span.

*Case 2.* We have a considerable length of 50-kv. pin type line consisting of three-phase wires and a ground wire all on the same crossarm at a uniform spacing of 42 inches. The phase conductors are each composed of three No. 8 wires, stranded, and the ground wire is the same size of steel. The wire was strung at 400 lb., 70 deg. fahr., and has developed several contacts on spans of 400 to 430 ft., crossing gullies in a rolling prairie country where the wind had an opportunity to cause eddies and other disturbances.

*Case 3.* We have personally observed a 1000-ft. span constructed similarly to Case 1 above and located at the top of a mountain ridge where a canyon led up to the top. Irregular blasts of wind coming over the canyon would cause the wires to deflect and in some cases this deflection would get sufficiently out of phase so that one wire would be practically in a vertical plane when the next wire was at nearly maximum horizontal deflection. We also observed that even under light wind, say, ten miles per hour, there were often irregular ripples running lengthwise over the wires. These ripples however, were not of great magnitude and could not have had anything to do with cause of contact between phases. The maximum ripple probably was not more than 18 in. Our observation leads to the conclusion that wires can be caused to swing out of synchronism to a considerable extent but we do not think it possible for two wires to swing in opposite directions at the same time under heavy wind conditions. Obviously, the greater danger of contact is in narrow valleys, or other broken topography, where the wind velocity is often excessive and also very turbulent.

As opposed to the cases of contact noted above, we have had spans 3200 ft. long at 22 ft. spacing strung at about 1200 lb. for ⅜-in. steel at 70 deg. fahr. over a straight smooth river channel, which were never in contact during 10 years of experience.

Yours very truly,
(Signed) A. C. Pratt."

NOTE: The 3200-ft. span described in the last paragraph would have apparently, a sag of approximately 15 per cent under the conditions of Class *A* loading. The formula would give for a copper conductor of the same size a horizontal spacing of over 40 ft. for a 110-kv. circuit, while no trouble was actually experienced with a 22-ft. spacing.

From another engineer there is a report that after experiencing trouble with all aluminum 3/0 and 4/0 cables on 500 ft. spans, with wires horizontally spaced 8 ft., with insulator string approximately 4 ft. long, this trouble being due to getting together of conductors in the span under the influence of wind, entire elimination of the trouble was obtained by the substitution of aluminum steel cable, 266,800 cir. mil, and 336,400 cir. mil, this being over a considerable length of line.

NOTE: If the sag with the aluminum steel cable be taken at 2 per cent, the formula would call for a 10-ft. spacing while no contacts have been experienced in many years with an actual 8-ft. spacing.

Extracts from report by Mr. V. M. McDonald, Supt., Transmission, Public Service Company of Colorado, received August 15th, 1927.

* * * * *

Span length, 400 ft.

Sag, 11½ ft.

Horizontal spacing, 10 ft. 6 in.

Voltage, 90,000.

Length of insulator string, 32 in.

Size and material of conductor, No. 1 hemp center copper strand.

Tension, 1150 lb.

Approximate wind velocity, (mi. per hr.), 85 at time of trouble.

Direction of wind with respect to conductor, right angles.

No sleet.

Location, side hill and nose slope.

When wires came together, circuit breaker tripped, conductor pitted.

This is the only known case where conductor came close enough to cause an arc. Wind was at right angles to line. Hillside deflected wind to an upcast underline that raised cables and they fell close enough to cause trouble.

We have several arcs between conductors on 44-kv., 4-ft. spacing triangle, due to burning weeds along railroad right-of-way.

NOTE: The last paragraph, while of value, does not relate to the swinging of conductors.

It is hoped that engineers interested in this matter will offer discussion on the above analysis, and will contribute any pertinent data they may have so that as much as possible may be assembled for the benefit of any who may have such horizontal constructions to install.

## Discussion

**M. G. Lloyd:** While Mr. Thomas has not attempted to give a complete analysis, he certainly has given us much food for thought on this problem. There is one thing I don't believe is made entirely clear. The tension in the conductor depends upon the loading condition. In the problems he has worked out, Mr. Thomas has taken the diameter of the wire bare, apparently, but has taken the loading with the ice on it. In other words, he has not taken the two constants that correspond one with the other. The tension in the wire, which is involved in deriving his formula, will depend, of course, on whether or not the wire is loaded.

From the discussion it seems to be clear that he considers the greatest danger of contact between the wires to be at the time of a wind with a vertical component acting upon the wire without ice upon it, and that seems a reasonable assumption as being the most dangerous condition. In working out the problems, however, he has taken the loading including ice on the wire, so that it doesn't seem to me his two conditions of diameter and of loading correspond to one another. I should think they both ought to be taken for the same condition.

Furthermore, in working out the examples on the fourth page, the author has assumed a definite percentage sag (percentage of span length). That percentage in practise, of course, varies with the span length and the values chosen would apply approximately for only a small range of span lengths. In the case of copper, for instance, where he takes the sag as 3.75 per cent of the span length, that would apply to a span length of, perhaps, 900 ft. or something in the neighborhood of that. For other span lengths that percentage would not be applicable and consequently, the results worked out would not seem to be applicable. He has not stated here what span length he is talking about. In working out these examples, if an entirely different span length is used, one gets results which are not at all comparable with practical values. For instance, if we take a very long span, the separations that are obtained by this formula, using that percentage of sag, come out in some cases entirely different from what would be considered practical values.

This formula, it is to be noted, brings in the first power of the sag as an element of the separation. I think experience has shown that more practical results are obtained by bringing in the square root of the sag rather than the first power. It is not clear just how that would be justified on theoretical grounds, as I do not see any imperfection in the author's reasoning to bring it in in the way that he does, but his formula will not be found very widely applicable when one considers a big variety of span lengths and the percentage sags corresponding to them.

In the statement on the fourth page, as to the application of the formula, the author says, "In comparing two spans, the horizontal spacing, other conditions than those specified being equal—," and he gives a list of a number of different conditions. As a matter of fact, you can't vary the things he mentions without varying the other quantities. It isn't a feasible, practical case to keep the other values constant when you vary those that he mentions.

For instance, in the first three cases, varying the tension, for instance, without varying the span length, the sag also will vary necessarily. You can't help but vary it or else vary the size of the conductor, which is another variable. That is true also if you keep the tension the same but vary the span lengths, which is the second case, or if you vary the tension and span length together, which is the third case. In the fourth and fifth cases, changing the diameter with the sag, span length, and loading the same, you will invariably change the tension. Of course, the tension doesn't appear explicitly in this formula, so that that does represent a case which is a practical one and the relations will be just as he has stated.

In the conclusions the author makes the statement, "The conditions will be worse in short spans and with small cables and large sags." I think in practise that doesn't work out because when you have the short spans you invariably have the small sags and probably high tension and you are consequently not likely to have trouble with short spans from this cause.

In the examples given in the letter quoted, the span lengths seem to run up to values that are not extremely high, but a thousand feet or so. I am sorry that in these examples of actual contacts that are cited there is nothing said about what the actual sag of these particular conductors was. If that could be given it would help to form some picture of the condition where these contacts have occurred.

On the fourth page where the values of actual separations of the Davis Bridge line and the Appalachian Power Company are compared to what is worked out in the formula, the sags do not appear to be given, so that it is difficult to determine how well they do fit the formula. It is possible that the percentage sag used in the examples worked out at the top of the page fit these particular cases that are mentioned but the data, unfortunately, are not given to check up on that point.

# Transmission Experience of the Public Service Company of Colorado

BY M. S. COOVER[1] and W. D. HARDAWAY[2]
Associate, A. I. E. E Associate, A. I. E. E.

***Synopsis.***—*The 100,000-volt transmission lines of the Public Service Company of Colorado, which were completed in 1909, extended from the Shoshone hydro plant on the Colorado River across the Continental Divide to Denver and represent pioneering in high-voltage transmission at high altitudes. This combination of factors, coupled with a rapid expansion of the whole system in recent years called for the satisfactory solution of many problems. The paper describes the system in a general way, and outlines some of the more salient operating difficulties that have arisen from time to time as well as their remedies. Brief mention is also made of the method of load dispatching.*

* * * * *

## INTRODUCTION

THE purpose of this paper is to submit the results of several years of operating experience of the high-voltage network of the Public Service Company of Colorado. Every transmission system has its own inherent mechanical and electrical features which are governed primarily by the amount of power to be transmitted, size of conductors, line voltage, spacing of conductors and towers, ratio of resistance and reactance and climatic conditions. Methods practised in load dispatching and the means of communication between various points on the system will vary for many reasons, depending largely upon local conditions and the best judgment of the engineers in charge. Furthermore, when any new problem in transmission engineering is encountered, or any change is contemplated, for the betterment of the service to be rendered it is always helpful to learn of the experiences of others who have been operating transmission systems.

A part of the transmission lines included in the present network operated by the company has been in continuous service for 20 years. Two years following this initial construction, the line was extended to a total length of 153.5 mi., from the Shoshone hydro plant on the Colorado River near Glenwood Springs across the Continental Divide to Denver, and from Denver to the Boulder hydro plant. Other sections of the network have been constructed during the past four years. With the exception of the transformers at the Shoshone hydro plant which were rebuilt last year, all of the original transformers and oil circuit breakers are still in service. This not only represents pioneering in the field of high-voltage transmission, but also progress in the art of design, construction, and operation. It is hoped that the data herein submitted will add to the information now available on such operating experience; also, that it may prove to be of some value to those having similar operating and maintenance problems.

## DESCRIPTION OF SYSTEM

The company serves the electric lighting and power requirements of practically all of the central, north central, and northeastern portions of Colorado. The area served covers approximately 750 sq. mi. and includes about 116,300 customers.

The high-voltage system comprises a total of 518 mi. of line at altitudes ranging from 5280 ft. to 13,700 ft. above sea level with 217 mi. of line operated at 100,000 volts and 301 mi. of line at 44,000 volts. The properties are segregated into what is known as the central system and the outside system, there being no means at present of interconnecting these two groups. Transmission in the central system is over 217 mi. of line at 100,000 volts and 181 mi. of 44,000 volts, and in the outside system transmission is all at 44,000 volts over 120 mi. of line. The map in Fig. 1 shows the territory served by both systems, as well as the location of the generating plants supplying these two principal transmission networks.

The generating plants connected to the central system, their capacity, and type of motive power are listed in Table I, while those of the outside system are listed in Table II. Since the outside system comprises only a small portion of the total properties operated by the company, the remaining material submitted in this paper will be confined entirely to the 100,000-volt transmission lines of the central system, a simplified diagram of which is given in Fig. 2.

The transformers supplying the 100,000-volt loop at Boulder Canyon and Valmont are star-connected, with the neutral solidly grounded. The step-down transformers at the Denver Terminal are delta-connected, on both high- and low-tension windings. The 100,000-volt transformers at Shoshone have been rewound recently for star operation on the high-voltage side, and the neutral has been solidly grounded. This connection has not yet been in service through a lightning season, and no data on the effect of this connection on flashovers are available. It has, however, greatly improved relay operation.

The 100,000-volt loop is equipped with impedance type protective relays, which have given correct sec-

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tionalization for about 95 per cent of the flashovers. Until recently, flashovers on the Shoshone line have been cleared by manually lowering generator voltage. Automatic equipment was installed in October, 1927, for lowering generator voltage by inserting a large block of resistance in the generator field circuit.

The switching center of the central system is the Denver terminal substation, located two miles within the city limits of Denver. Three 100,000-volt lines converge there, and 60,000 kv-a. in transformer capacity is provided for supplying 13-kv. city feeders. The system operator and dispatching office are located at this substation. Private telegraph and telephone, and leased telephone lines are provided for communication with all parts of the central system.

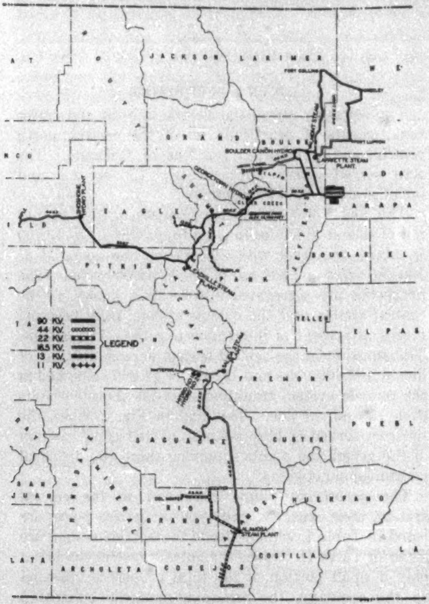

JACKSON
LARIMER
FORT COLLINS
GRAND
BOULDER
BOULDER CANON HYDRO
LAFAYETTE STEAM PLANT
ADAMS
EAGLE
SHOSHONE HYDRO PLANT
CLEAR CREEK
ARAPAHOE
PITKIN
PARK
DOUGLAS
TELLER
EL PASO
FREMONT
CHAFFEE
SAGUACHE
CUSTER
HINSDALE
MINERAL
RIO GRANDE
ALAMOSA STEAM PLANT
HUERFANO
COSTILLA
ARCHULETA
CONEJOS
90 KV.
44 KV.
22 KV.
16.5 KV.
13 KV.
11 KV.
LEGEND

Fig. 1—Territory Served by the Public Service Company of Colorado

## Altitude—Weather Conditions

The 100,000-volt line which crosses the Continental Divide presents a most difficult task of maintaining a high degree of continuous service. Reference to the profile of this line as shown in Fig. 3 discloses that the line originates at an altitude of approximately 6000 ft. at the Shoshone hydro plant; then traverses the Rocky Mountains, negotiating three passes—Hagerman at 12,000 ft., Freemont at 11,500 ft., and Argentine at 13,700 ft., thence to the Denver Terminal at 5280 ft. above sea level.

Shortly following the completion of this line, many interesting experiments were conducted and some of the results have appeared in Institute papers. The weather conditions during the winter season are very severe, making it difficult to secure all the operating data which often would be desired in cases of trouble. At the higher altitudes in the fall and spring there is an abundance of moist winds, whereas in the winter temperatures as low as 52 deg. below zero fahr. have been recorded. The maximum measured wind velocity so far reported is 165 mi. per hour. These conditions, combined with the heavy snows, make certain sections of the line almost inaccessible for a period of time, which means that the line must be thoroughly dependable from both the electrical and mechanical standpoint.

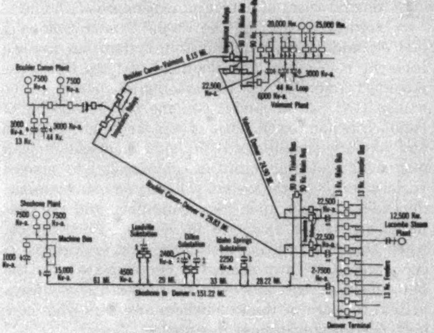

Boulder Canon Plant
7500 Kv-a.
7500 Kv-a.
3000 Kv-a.
13 Kv.
3000 Kv-a.
44 Kv.
Boulder Canon—Valmont 8.15 Mi.
20,000 Kw.
25,000 Kw.
22,500 Kv-a.
3000 Kv-a.
44 Kv. Loop
6000 Kv-a.
Valmont Plant
Valmont—Denver = 24.95 Mi.
Boulder Canon—Denver = 29.83 Mi.
Shoshone Plant
7500 Kv-a.
7500 Kv-a.
Machine Bus
1000 Kv-a.
15,000 Kv-a.
Leadville Substation
4500 Kv-a.
Dillon Substation
2400 Kv-a.
Idaho Springs Substation
2250 Kv-a.
61 Mi.
29 Mi.
33 Mi.
28.27 Mi.
Shoshone to Denver = 151.27 Mi.
90 Kv. Main Bus
22,500 Kv-a.
22,500 Kv-a.
2-7500 Kv-a.
13 Kv. Main Bus
13 Kv. Transfer Bus
12,500 Kw. Lacombe Steam Plant
13 Kv. Feeders
Denver Terminal

Fig. 2—Simplified Diagram of the 100-Kv. Lines of the Public Service Company of Colorado

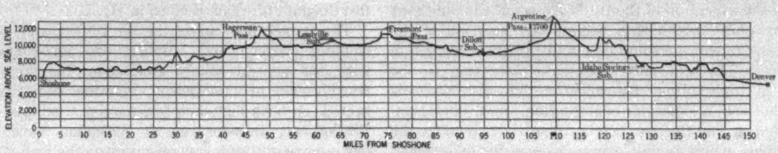


Fig. 3—Profile of Transmission Line, Shoshone to Denver; Denver to Boulder

There are times when the winds are heavy-laden with moisture which freezes as it strikes the cold surfaces of the towers and conductors. This frost formation which usually builds out against the wind has been found to cover the conductors with an over-all dimension of 12 in., with still greater masses on the towers. Frost formations measuring 2 to 2½ ft. in thickness have been observed on the towers but so far there has been no failure of towers on account of this loading. Fig. 4 shows an interesting view of this ice formation; also the method of holding the jumpers in place against the high wind velocity. This particular tower stands at the top of Argentine Pass.

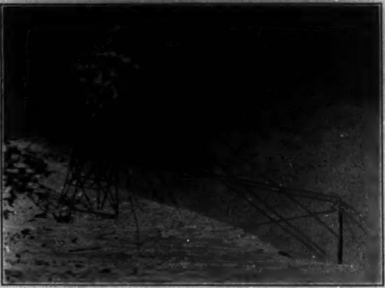


Fig. 4—Tower on Argentine Pass. Altitude 13,700 Ft.

One of the important factors taken into account in locating the tower line were snow and rock slides. Whenever it appeared unlikely to avoid these slides, heavy cribs were built around the towers to prevent their destruction. Fig. 5 shows the method adopted to protect the towers from such slides. The cribs are constructed V-shape and on the up-hill side of the tower, the intention being to split the slide. This type of protection, illustrated in Fig. 5, is constructed of heavy steel section securely anchored and filled with rock. During the nearly 20 years that the lines have been in operation, only ten tower failures have occurred attributable to slides. Of this number, one failure resulted in both the protecting crib and its tower being carried away by the slide. Landslides also have been the cause of several tower failures.

Considerable lightning is encountered on this line, covering an average period of 130 days per year. Many statements are made to the effect that insulation is the foundation of the electric power system; and true it is; yet any line exposed to storms, lightning, and slides, as previously mentioned, calls for a high degree of sturdiness in both electrical and mechanical design. The line across the Continental Divide has been in operation sufficiently long to enable a satisfactory solution to most of the mechanical problems in maintenance, but the problem of protection against lightning is still a very difficult one to master reasonably.

TABLE I.
GENERATING PLANTS—CENTRAL SYSTEM

| Location | Rated kw. at 0.8 p. f. | No. of units | Motive power |
|---|---|---|---|
| Shoshone | 14,400 | 2 | Water |
| Boulder Canyon | 14,400 | 2 | Water |
| Georgetown | 900 | 2 | Water |
| Leadville | 1,925 | 2 | Steam |
| Lafayette | 6,000 | 4 | Steam |
| Denver (West Plant) | 9,250 | 4 | Steam |
| Denver (Lacombe Plant) | 16,500 | 3 | Steam |
| Valmont | 45,000 | 2 | Steam |

TABLE II
GENERATING PLANTS—OUTSIDE SYSTEMS

| Location | Rated kw. at 0.8 p. f. | No. of units | Motive power |
|---|---|---|---|
| Cheyenne | 4,000 | 4 | Steam |
| Sterling | 2,250 | 3 | Steam |
| Alamosa | 1,400 | 2 | Steam |
| Salida | 700 | 2 | Steam |
| Salida | 1,200 | 5 | Water |

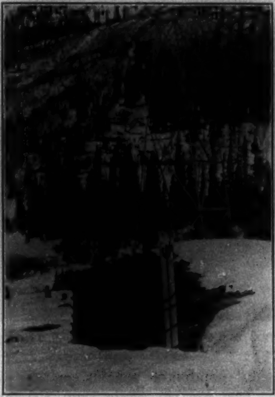


Fig. 5—Crib Protecting Tower from Snow and Rock Slides

### Line Insulation

The original insulation was four Hewlett disk insulators on both dead-end and suspension strings with a 7½-in. spacing of disks on the dead-end and 6-in. spacing on the suspension strings. The ratio of dead-ends to suspensions was about one to fifteen. Two ¼-in. steel ground wires were put up for protection. Many difficulties were encountered during the first year of operation, principally on account of the lines being under-insulated and on account of mechanical failures of the ground wires. During the following year, the ground wires were removed, and a fifth disk was added to all dead-ends. This measure showed some improvement in service. During the following year, arc points were placed on both ends of all strings to provide a flashover path which did not destroy insulators. However, they do not reduce the number of outages caused by lightning.

In 1916, it was decided that the flashovers per annum were still too numerous, whereupon a fifth disk was added to all suspension strings and a sixth disk to all dead-ends. This reduced the number of flashovers approximately 75 per cent.

### NEW 100-KV. LINES

The Valmont-Denver line and the Valmont-Boulder line (see Fig. 2) were built during 1924, and placed in service during December of that year, which also marked the completion of the first unit of the new Valmont steam plant. These two lines tie in the plant with the Denver Terminal and with the Boulder Canyon hydro plant. American Bridge Company towers were purchased for both lines and designed for single circuit horizontal conductor spacing on the Valmont-Boulder tie, (see Fig. 6), while twin circuit vertical conductor spacing is used on the Valmont-Denver tie. Only one circuit was strung on the latter tie, and the second circuit will be added when the growth in load reaches such a point as to demand it.

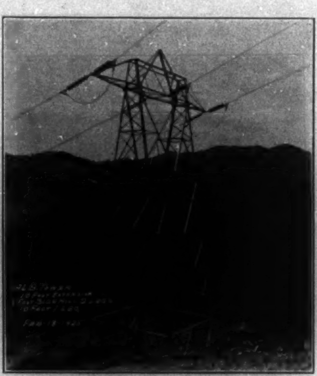


FIG. 6—TYPE OF TOWER USED ON VALMONT—BOULDER LINE

High mechanical strength, 336,000-cir. mil, A.C.S.R. conductors are used on both tie lines, the cable being made up of 30 strands of aluminum 0.1059 in. in diameter and 7 strands of steel 0.1059 in. in diameter. All suspension strings consist of seven No. 25622 O-B insulators spaced 4¾ in., and all dead-end strings consist of seven No. 26240 O-B insulators spaced 7 in. Arc points were initially placed on suspension clamps and at dead-end points on all strings, hoping to avoid breakage of upper disks by flashovers. Fig. 7 shows a typical failure of upper disk, and Fig. 8 shows type of upper arc points which are being installed.

### GROUND WIRES

Before going into a discussion of the interruptions to service on the 100,000-volt lines, it would be well to review the company's experience with ground wires. In the original design of the Shoshone-Denver and the Boulder-Denver lines, two ground wires were incorporated in an effort to avoid lightning troubles. These ground wires were soon abandoned and taken down on account of mechanical difficulties as previously mentioned. All towers on the new tie lines to the Valmont plant are so constructed that a ground wire may be added readily, but to date this has not been done.

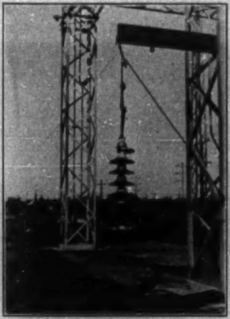


FIG. 7—UPPER DISK FAILURE WHEN NOT PROTECTED BY ARC POINTS

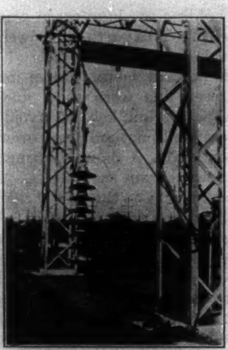


FIG. 8—TYPE OF UPPER ARC POINTS BEING INSTALLED

The lines from the Shoshone and Boulder hydro plants and the Valmont steam plant converge at a point about four miles west of Denver. From the Dry Creek substation, 2½ miles west of the terminal, the circuits from the Boulder and Valmont plants are carried on a double circuit tower line, the construction of which is illustrated in Fig. 16; while the Shoshone circuit is brought the same distance over a single circuit H-frame wood pole line, all on a common right-of-way. This double circuit of 2½ miles in length has been protected with a ground wire through two lightning seasons, with the result that there has been no insulator breakage on account of flashovers, and it is believed that there have been no flashovers during this period on this particular section.

### TYPES OF TOWERS

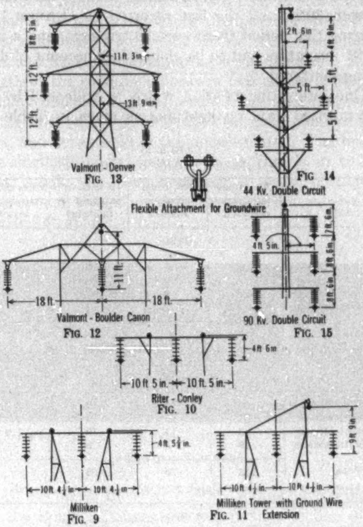
The Shoshone and Boulder Canyon lines were built on two types of towers, as indicated in Figs. 9 and 10. The tower shown in Fig. 10 was originally intended for double circuit use, with the second circuit directly below the upper circuit. This arrangement was found impracticable, and the lower arm was removed. Both of these towers were originally equipped for two ground wires, with clamps located at the connection of tower legs and the upper arm. Spacing was inadequate and ground wire failures were frequent, so they were taken down shortly after construction. Fig. 11 shows an extension recently added for carrying a ground wire over a portion of the Boulder line. The ground wire is flexibly supported in a standard conductor suspension clamp. The tower shown in Fig. 10, with a height of 50 ft. weighs 3600 lb. Fig. 9, 44 ft. high, weighs 1980 lb. In the Boulder Canyon–Valmont line built in 1924, the tower shown in Fig. 12 was used. It weighs 6000 lb., with a height on top of insulator string of 41 ft. The Valmont-Denver towers, Fig. 13, double circuit, built in the same year, weigh 7600 lb.

The tower shown in Fig. 9 appears to be very light and of flimsy construction, and guys are used on many towers. However, few tower failures have occurred. The somewhat flexible construction of these towers has probably relieved the stresses on them, and has permitted the guys to take some stress before tower members failed.

The steel poles, shown in Figs. 14 and 15, were used where right-of-way difficulties required narrow base construction.

### INTERRUPTIONS

Such information as has been recorded which may enable an analysis of the causes of interruptions is summarized in Table III. The data on outages have not been recorded with the degree of completeness which might be followed were a special study to be conducted on this phase of operation. The number of broken


8ft. 3in.
11ft. 3in.
12ft.
13ft. 9in.
12ft.
Valmont - Denver
FIG. 13
2ft. 6in.
4ft. 9in.
5ft.
5ft.
5ft.
FIG 14
44 Kv. Double Circuit
Flexible Attachment for Groundwire
7ft. 6in.
4ft. 5in.
8ft. 6in.
8ft. 6in.
11ft.
18ft.
18ft.
Valmont - Boulder Canon
FIG. 12
90 Kv. Double Circuit
FIG. 15
4ft. 6in.
10ft. 5in.
10ft. 5in.
Riter - Conley
FIG. 10
4ft. 5¼ in.
10ft. 4½ in.
10ft. 4½ in.
Milliken
FIG. 9
9ft. 9in.
10ft. 4½ in.
10ft. 4½ in.
Milliken Tower with Ground Wire Extension
FIG. 11

FIGS. 9—15

TABLE III

SUMMARY OF INTERRUPTIONS

| Line—Year | Spacing | Lightning | Operating error | Plant or sub-station trouble | Secondary trouble | Jumper off | Slides | Wind | Rifle shooting | Birds | Unknown | Total line | Total year | Broken conductors |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1925 | | | | | | | | | | | | | | |
| Shoshone-Denver.... | Flat | 49 | 0 | 6 | 1 | 0 | 1 | 8 | 0 | 0 | 4 | 69 | | 6 |
| Boulder-Denver...... | Flat | 6 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | | 1 |
| Valmont-Denver..... | Vert. | 6 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 8 | | 0 |
| Valmont-Boulder .... | Flat | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | 0 |
| | | | | | | | | | | | | | 85 | |
| 1926 | | | | | | | | | | | | | | |
| Shoshone-Denver.... | Flat | 46 | 1 | 3 | 4 | 1 | 0 | 1 | 0 | 0 | 7 | 63 | | 2 |
| Boulder-Denver...... | Flat | 10 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 13 | | 0 |
| Valmont-Denver..... | Vert. | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14 | | 0 |
| Valmont-Boulder .... | Flat | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | | 0 |
| | | | | | | | | | | | | | 91 | |
| 1927 | | | | | | | | | | | | | | |
| Shoshone-Denver.... | Flat | 35 | 0 | 2 | 5 | 3 | 5 | 5 | 1 | 0 | 4 | 60 | | 5 |
| Boulder-Denver...... | Flat | 8 | 0 | 0 | 0 | 1 | 0 | 3 | 0 | 0 | 0 | 12 | | 1 |
| Valmont-Denver..... | Vert. | 11 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 2 | 15 | | 0 |
| Valmont-Boulder.... | Flat | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | | 1 |
| | | | | | | | | | | | | | 89 | |

conductors as given in the last column of Table III for each line during each year, are included in their proper places under other headings in the table. In some instances the failure was attributed to wind, while in other instances, the cause was not definitely apparent.

The prevalence of thunderstorms in the mountain regions causes many interruptions on account of lightning. The number of outages from this source amounted to 71.8 per cent in 1925; 77.8 per cent in 1926; and 62.9 per cent in 1927. The lightning report of the company for 1927 gives a total of 228 thunderstorms accompanied by a quantity of lightning, the first reported on March 30th, and the last reported on October 12th. During this period there were 56 trip-outs, and a total of 91 insulators had to be changed on account of disks being shattered.

One interesting relation which is evidenced by the summarized data on lightning as given in Table IV, is the comparison of the "miles of circuit per trip-out per lightning season" for the several 100-kv. lines. Bearing in mind the fact that these circuits are not protected by a ground wire except for the 2½ mi. of vertical-spacing double circuit from the Dry Creek substation into the Denver Terminal, the conclusion to be drawn is that flat construction without ground wire is least disturbed by thunderstorms. Following the observations which have been made to date on this particular phase of operation, the company decided that a ground wire properly installed is an essential adjunct to the system, and is proceeding with its construction, due attention being given to its material, location, method of attachment, and stringing tension.

TABLE IV
SUMMARIZED LIGHTNING REPORT

| Line | No. times lightning reported | No. times breakers opened | No. insulators damaged by lightning | Miles ckt. per trip-out per season |
|---|---|---|---|---|
| | | 1925 | | |
| Shoshone-Denver | 106 | 49 | 33 | 3.1 |
| Boulder-Denver | 44 | 6 | 14 | 5.0 |
| Valmont-Denver | 25 | 6 | 6 | 4.6 |
| Valmont-Boulder | 8 | 0 | 5 | — |
| Total....... | 183 | 61 | 58 | |
| First lightning reported April 6th; last reported November 13th. | | | | |
| | | 1926 | | |
| Shoshone-Denver | 153 | 46 | 19 | 3.3 |
| Boulder-Denver | 61 | 10 | 12 | 3.0 |
| Valmont-Denver | 23 | 14 | 10 | 1.9 |
| Valmont-Boulder | 18 | 0 | 9 | — |
| Total....... | 255 | 70 | 50 | |
| First lightning reported March 20th; last reported October 4th. | | | | |
| | | 1927 | | |
| Shoshone-Denver | 130 | 35 | 38 | 4.6 |
| Boulder-Denver | 47 | 8 | 20 | 3.7 |
| Valmont-Denver | 25 | 11 | 23 | 2.5 |
| Valmont-Boulder | 26 | 2 | 10 | 4.0 |
| Total....... | 228 | 56 | 91 | |
| First lightning reported March 30th; last reported October 12th. | | | | |

The ground wire is flexibly suspended from "U" bolts or eyes in a standard conductor clamp and in a position where it is free to swing. In other words, instead of treating it merely as a doubtful appendix to the circuit, it is receiving the same careful consideration as though it were one of the main conductors.

In all but two cases where insulator damage occurred on the Valmont-Denver line as a result of lightning, the damage was confined to the string supporting the top conductor. This is in line with results to be expected on vertical type construction.

Table III indicates that substation troubles have somewhat frequently affected transmission line operation. Occasional 100-kv. bus flashovers occur in the indoor substations, although the busses are separated by twice the flashover distance between line insulator arc points. These troubles appear to be most frequent in the substations at Dillon and Leadville, which are approximately 9500 and 10,500 ft. above sea level respectively. Grounding the line neutral seems to have largely eliminated this trouble.

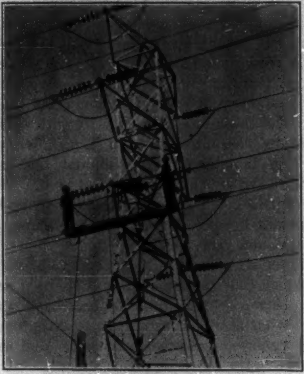


FIG. 16—TYPE OF DOUBLE-CIRCUIT TOWER

### INSULATOR FAILURES

When the new lines were built, seven close-spaced disks were used in suspension, with the expectation that cascading on flashovers would be avoided. Arc points were provided on the suspension clamp to avoid burning of the conductor. Operating experience indicates that practically all flashovers damage one or more insulator disks at the top of strings. A theory has been proposed by the insulator manufacturers that the swinging bracket used for mechanical reasons in supporting suspension strings causes a detrimental distribution of electrostatic flux. Upper arc points are being installed at all points to protect the insulators from flashover arcs.

It is of interest to note that in the 50 flashovers which have occurred on the new lines, in all but one case it has been possible to restore service immediately without repair or insulator replacements. In the one case excepted, insulator hardware was burned through on account of a relay failure, and the conductor was dropped. This string is shown in Fig. 17.

### CONDUCTOR FAILURES

The failure of power conductors and ground wires as a result of vibration is a subject which has received considerable attention in recent years. Efforts have been made to determine those factors which contribute to destructive vibration and valuable data have been assembled. Within its lifetime of operation the Public Service Company of Colorado has experienced approximately 200 conductor failures attributed to various causes. The majority of these cases of trouble occurred in the early years of operation and repetition was prevented by the use of a flexible joint between the conductor and the insulator for suspension type construction and at the towers for dead-ends.

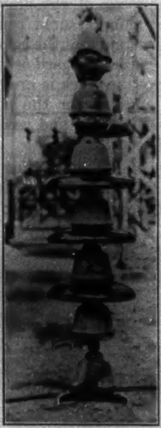


FIG. 17—INSULATOR HARDWARE BURNED THROUGH

One interesting and peculiar type of conductor break began to develop in 1921 for the first time and has been showing up since at an increasing rate. Horizontal spacing is used on the Shoshone-Denver and on the Boulder-Denver lines, these lines having been constructed in 1909. All conductors as initially installed consisted of six copper strands with hemp center. Referring to the profile in Fig. 3, No. 1/0 conductor was strung from Shoshone to Leadville; No. 1 conductor from Leadville to Dillon; No. 1/0 conductor from Dillon to Denver, and No. 1 conductor from Boulder hydro plant to Denver with a tension of 1250 lb. at 60 deg. fahr. Steel towers are used the full length of these lines, with a normal span length of 700 ft., a minimum of 300 ft., and a maximum of 2700 ft. The general direction of the wind is parallel to the Shoshone-Denver line and at right angles to the Boulder-Denver line.

The probable phenomenon surrounding the type of failure which began to show up on the Boulder-Denver line in 1921, and not until in the spring of 1927 on the Shoshone-Denver line, has aroused much concern for the reason that it has been necessary to replace 11.4 line mi. of conductor to date on the Boulder-Denver line on account of failure of individual strands. A close examination of the breaks in the individual strands reveals that some strands fail from crystallization, some from elongation, and some from an apparent crystallization. If the length of the conductor between two points is divided roughly into thirds, these breaks occur most frequently in the third of the span length next each point of support, and very rarely in the middle third. The breaks in a single strand are found to occur from ½ in. to 4 in. apart, while these breaks appear to be in a stage of development along the conductor grouped at intervals of 6 in. to 6 ft. apart.

FIG. 18 FIG. 19 FIG. 20

STRAND FAILURES

All but one of these conductor failures have occurred on the Boulder-Denver line and in that section of the line which traverses what is known as the Rocky Flats, just north of the city of Golden, where the prevailing severe winds are at right angles to the transmission line. From observation, it is found that in addition to the swinging of an entire span length of one conductor, there are segmental vibrations set up. These segmental vibrations promote crystallization, which in time develops a slight fissure in the strand next to the hemp center. Then there is a possible electrolytic action set up following the creation of the fissure, the metal being conducted through a film of moisture and deposited on the hemp center. This line of reasoning does not always appear to be borne out by facts; for while there is a noticeable deposit of copper on the hemp center in some instances, there are other instances in which the hemp is very badly disintegrated with no sign of copper deposit and still others where the hemp is in a high state of preservation with no sign of copper deposit. Another thought which has been advanced is that the wire as received from the mills contains slight flaws which progressed under vibrational stress. Neither theory seems to provide a satisfactory answer.

The appearance of a strand failure enlarged to approximately 20 diameters may be seen in Figs. 18, 19, and 20. These particular ones are three of a total of four strands in a conductor break having the same characteristic appearance, while the other two strands of the conductor failed as a result of elongation with a slight amount of burning as the conductor finally parted. All six strands parted within a distance of 11 in. along the conductor. It will be noted that a very definite crater exists, partly as a result of the disappearance of metal, and partly on account of the necking down of the small amount of metal left around the periphery of the strand. These three illustrations are typical of all those investigated where the fissure had progressed nearly all the way across the strand.

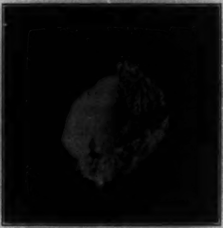


FIG. 21—STRAND FLAW DISCOVERED AFTER CONDUCTOR WAS REMOVED FROM LINE

Fig. 21 shows an enlargement of a break completed by hand. As the strand was unwound from the conductor it parted with less effort than the breaking of a thin toothpick. In other words, it virtually fell apart, so high was the degree of disintegration. The break was a little more uneven than in the three preceding illustrations, and could not be focused uniformly. It may be seen, however, that the fissure had progressed more than a quarter of the way across the strand with the same characteristic stream lines converging at a point of discharge as in the other strands, and that the process of creating the defect is in two stages; one progressing V-shape and the other in the shape of a fan.

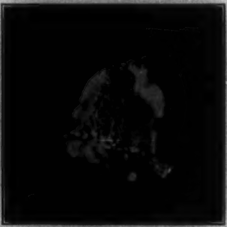


FIG. 22—STRAND FAILURE PRODUCED MECHANICALLY

Fig. 22 is an enlargement of a strand break produced mechanically and submitted only to compare its fracture with those produced in line service. It may be mentioned that the reason the enlargements do not appear to be more circular is on account of the fact that the specimens had to be tilted slightly under the lens in order to use reflected light. A fact of some note is that, to date, the phenomenon described above has only occurred on the No. 1 size conductor, there being none to date on the No. 1/0 conductor.

Another reason which may be advanced for these failures is that the process of wire drawing in use at the time the cable was manufactured resulted in the wire being drawn too hard, and that the conductor vibrations set up by the wind causes any hard or brittle spots in the wire to crack. Once the crack is produced, it is only a question of time until under the possible combined influence of corona discharge and repeated flexure, the ultimate break will occur.

The abrupt rise of the mountains from the plains produce a change in temperature sufficient to keep air currents crossing the Boulder-Denver line almost continuously. It has been observed that even slight air currents will set up and maintain vibrations which appear to have a greater amplitude at times than the segmental vibration caused by high winds. It is regretted that no specific data have been obtained on these lines which might enable some possible relation to be established among temperatures, length of span, stringing tension, frequency and amplitude of vibration.

FIG. 23—PACK TRAIN USED ON CONSTRUCTION AND MAINTENANCE

To date no vibration troubles have been experienced on the aluminum conductors.

## MAINTENANCE AND OPERATION

Maintenance methods have been developed which enable the patrol men to make repairs with the minimum of assistance. This has been made necessary by the inaccessibility of many parts of the line. Fig. 16 illustrates the working platform and "slack puller." The platform is suspended from the arms and guyed to the base of the tower. It provides a stable platform at a convenient height for work on dead-ends, and is safe even in high winds. When necessary, hook ladders and planks temporarily attached to the towers are used for work on suspension strings.

The "slack puller" is a crank-operated tension device with sufficient gear reduction to enable one man to exert a tension of 10,000 pounds. Its use dispenses with heavy blocks and luff lines in insulation replacement work. This device was invented and patented by the Transmission Superintendent of this system.

In the mountainous regions where the line can be reached only over steep, rocky trails, burros are used in pack trains for transporting material. Fig. 23 shows this means of transportation.

### SAFETY IN OPERATION

There has been no fatal accident to any employee on the 100-kv. lines during the entire period of operation. One man was seriously injured in a fall from a temporary platform because he was not using his safety belt. There have been two accidents fatal to men not employed by the company. One occurred when a young soldier climbed a tower on a dare and fanned the conductor with his hat. The second accident killed a sheep herder and his horse when he rode into a line having insufficient clearance.

Grounded guard wires have been installed under the lines at important highway crossings, and the towers have been fenced or otherwise guarded in places which are particularly accessible.

Responsibility for safe operation of the lines rests largely with the dispatchers. Patrolmen keep the dispatcher informed of their movements, and when patrolmen do not report on schedule, additional help is sent out. This protection is particularly necessary in mountainous country where blizzards are not infrequent, and where falls or snow slides may disable men.

Safety and first-aid work is emphasized, and a wholehearted attempt is made to "sell" the idea of doing work safely, rather than to enforce rigid rules of safe conduct. Monthly meetings are held where safety and operation are discussed, and where any employee may voice pertinent ideas or opinions.

Linemen are divided into groups and if no time is lost on account of accidents to any member of the group in a three months' period, each member is given a pair of pliers, suit of overalls, pair of gloves, or similar useful article.

### CONCLUSIONS

No exceptional difficulties have been encountered in high-altitude operation; jumpers at dead-end towers should be supported where wind velocities are high.

Insulation problems are no more serious than at sea level.

Arc points appear to be desirable at both ends of insulator strings. Copper and steel conductors operating above the critical voltage for corona for many years do not show unusual depreciation.

Horizontal configuration appears to be more desirable than vertical configuration, and properly built ground wires are probably effective.

Satisfactory relaying of high-voltage lines has been accomplished without great difficulty.

## Discussion

**Harold Michener:** Some of the conductor failures were said to be due to wind, or thought to be due to wind. I should like to ask if it was thought that the wind forces caused those conductors to part without burning or whether it was the wind that blew the conductors into the tower or the two conductors together, after which they burned down.

**M. T. Crawford:** The Puget Sound Power & Light Company has operated a 120-mi., 110-kv. line across the Cascade range for about six years. Although the altitudes are not as great as those described in this paper, the ice and snow formation and weather conditions appear equal if not worse. The experiences on this line were described in a paper presented at the Pacific Coast Convention of the Institute in October, 1923.[1] Subsequent to the presentation of this paper, additional reconstruction work was done, following which there have been five years of very successful operation without a *single* interruption due to failure in the extreme loading section.

As finally reconstructed this line is built on standard steel towers with horizontal conductor arrangement, using 350,000 cir. mil 19-strand hard-drawn copper cable. No dead-ends are employed, all wires being held by suspension strings, each consisting of two standard strings yoked together in parallel, and free to swing at both tower and clamp. This method of construction permits free movement of conductors lengthwise of the line and eliminated the troubles which were first experienced from wires being jerked in two at dead-ends by the falling off of large sections of the snow and ice formation which builds up to 2 ft. in diameter.

All of the diagonal and horizontal angles were removed from the steel towers up to the snow line and in their place heavy angles were installed paralleling the corner leg members, eliminating the serious trouble which was at first encountered by the bending and shearing of angle braces by the settling of the heavy snow crust in the Spring.

Fortunately lightning is infrequent in the Puget Sound region. Only six interruptions have occurred in the five years from troubles of all kinds on this line, two of which were from lightning.

I should like to ask the authors of this paper if the troubles from broken conductors on the Shoshone-Denver line, noted in Table III, included any breakage of the character referred to above, due to the ice loading or to jerking action at times of dropping off of such loading.

**H. H. Plumb:** I should like to ask the authors if they have evidence of any unusual wind velocity at the high points across the passes. In my experience the evidence has been very plain that the wind velocity at the top of a fairly high mountain has been exceptionally high, of the order of a hundred miles per hour. That figure has been obtained by taking the size of the ice coating at the time when failures occurred, which was about 4 in. in diameter on a ⅜-in. diameter conductor of steel, and calculating the wind velocity that must have been present to break such conductors.

I should like to ask the authors if they have encountered any such high wind velocities as that.

**G. B. McCabe:** I wish to question the wisdom of leaving that word "probably" in the conclusions under the next to the last paragraph—"properly built ground wires are probably effective."

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[1] *Transmission Line Construction in Crossing Mountain Ranges*, M. T. Crawford, TRANS. A. I. E. E., Vol. XLII, 1923, p. 970.

In the case of the Detroit Edison Company, we should leave the word "probably" out of such a statement.

We have a section of a double-circuit, 120,000-volt line between Trenton Channel and Marysville power houses, which runs through a particularly bad area in respect to lightning. During the 1925 lightning season on this double-circuit line in this particular section between Marysville and Superior Substations we had 44 lightning storms and 107 trip-outs. The following Winter we equipped the bad section with ground wire, a single ground wire of the same size as the conductors, *viz.*, No. 000 supported in the peak of the tower, and during the next or 1926 lightning season, with 34 electrical storms we had only seven trip-outs. We therefore feel that the use of ground wires is decidedly effective.

**W. D. Hardaway:** Mr. Michener asked if wind forces caused the actual failures. My impression is that they did not. I think that at the time the worst trouble was being experienced the line was equipped with ground wire at that point and the conductor was blown into the ground wire and burned, or at least nicked, and failed later.

Mr. Crawford's discussion was certainly an "eye-opener" to the operators in Colorado. Our snow loading and ice loading isn't as severe as that. We have large volume of frost formation but it isn't very heavy. Also, his service record of six outages in five years was certainly very interesting to us.

As to failures by jerking action of ice loading, I don't believe that has been experienced for the reason that the ice loading is not very dense. It is sometimes a foot in diameter but not heavy. Some of the failures which have occurred have been where the line was buried under snow and the snow suddenly settled and took the line out. It is rather interesting that some of those lines have operated actually under the snow, through tunnels in the snow.

Mr. Lloyd spoke of whipping of conductors on the Argentine Pass. The particular experience given in Mr. Thomas' paper was obtained on another line, Boulder Canyon, on a very steep hillside, and with a lighter conductor than the line across Argentine. However, there has been some wind trouble at Argentine which was helped by dropping the middle conductor and obtaining increased separation vertically.

The wind velocities which were mentioned are of interest to us. I can't speak with definite knowledge, but we have reports of 150-mi. wind velocities on Argentine Pass. Of course, those velocities should be corrected to sea level. They do not have as destructive action at 13,000-ft. altitude as they would have at sea level.

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# A-C. Elevator Motors of the Squirrel-Cage Type

BY E. E. DREESE[1]
Member, A. I. E. E.

***Synopsis.**—This paper sets forth the features of squirrel-sage motor design which differentiate it from standard motors. Much of the paper is devoted to the two-speed motor with two separate stator windings having speed ratios of 2/1, 3/1, 4/1, and 6/1. The two-speed motor with a single winding is limited to the 2/1 ratio. Higher ratios are necessary for high elevator speed and low and accurate landing speed.*

*The elevator motor is subjected to continual starting and stopping. The effects of inertia in such service are considered in connection with motor heating.*

*The proper division of slot area between the two stator windings and the problem of building a rotor with proper characteristics on both speeds are explained.*

*Noise elimination is necessary in elevator motors. The effect of this requirement in design is considered.*

*The effect of rotor skew is compared to the effect of distributed winding in the stator. The quantitative effect of skew is embodied in a constant called "skew factor."*

*The possibility of transformer effects between the windings of a two-speed motor is explained and methods of correcting to eliminate circulating currents are indicated.*

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THE induction motor as developed for elevator drive is a highly specialized type of machine. Slip-ring motors have been used, but the complications of control and the difficulty in eliminating noise have caused them to give way to the high-resistance squirrel-cage type. The high-resistance rotor gives a speed-torque characteristic which insures that the motor will have no points of mechanical instability and the motor will not pull-out and stall. The high-resistance rotor can be designed to give the maximum torque when starting and the torque per ampere is high. Another advantage of the high-resistance rotor is that it reduces the stator heating during a change of speed.

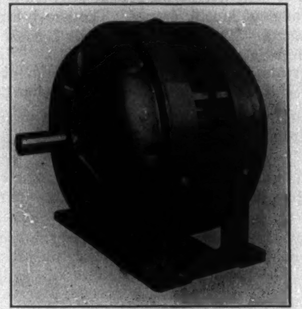

FIG. 1—SQUIRREL-CAGE TYPE ELEVATOR MOTOR

For a low-speed elevator the stator is usually wound for a single speed. For higher speeds the motor is built for two speeds since at high elevator speeds it is more difficult to make accurate landing. In the case of two-speed motors, the high-speed winding is generally used for starting and running and the low-speed for retarding and landing. The speed ratio required for the two windings should be greater the higher the speed of the elevator. Common speed ratios are 2-1, 3-1, 4-1, and 6-1. The high speed usually has four poles or more and the low speed 48 poles or less. A common motor for high-speed elevators has eight poles on the high speed and 48 poles on the low speed, running at synchronous speeds of 900 rev. per min. and 150 rev. per min. respectively on 60 cycles. The speed-torque and current-torque curves of two representative motors are shown in Figs. 2 and 3.

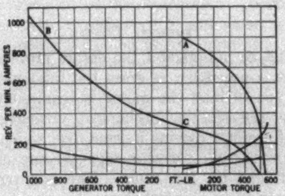

FIG. 2—TORQUE AND CURRENT CHARACTERISTICS OF 3-1 ELEVATOR MOTOR

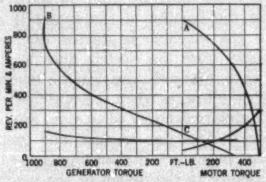

FIG. 3—TORQUE AND CURRENT CHARACTERISTICS OF 6-1 ELEVATOR MOTOR

Performance calculations on the high-speed winding are much simpler than on the low-speed winding. The conventional methods of calculation by the use of the circle diagram are possible only with the higher speeds. With the lowest speeds such as with 48 poles, the con-

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[1] Chief Engineer, Lincoln Electric Co., Cleveland, Ohio.

*Presented at Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

ventional circle diagram cannot be used. The reason is that the stator winding has high resistance and reactance characteristics due to the large number of turns of relatively small wire required. The idle current is practically the same as the starting current. There is a method of using a circle diagram for this type of motor in which diagrams the circle is displaced and tipped from its ordinary position. This method has been described by Behrend and makes use of McAllister's Transformations. But this graphical method has not been found convenient and expeditious for design work. Calculations using the constants of the circuits have proved much less laborious.

These motors are wound for star connection but the leads going to the neutral are brought out of the machine separately instead of being connected inside. This allows the user to insert resistance for starting, if desired, at the neutral point where the voltage between phases is low and the insulation problem in the control is thereby made simple. With this arrangement the wiring arrangement of the control is likewise simplified.

### INERTIA LOADS

In order to understand the design problems in this motor, it is necessary to grasp the fundamental ideas of the type of load the motor is required to handle. Consider the simple mechanical arrangement consisting of a motor driving a drum over which is hung a cable carrying an elevator cage on one end and a counterweight on the other. The counterweight is usually enough to counterbalance the weight of the cage and a certain portion of the capacity load. This portion is usually in the neighborhood of 40 per cent. Thus, with a load of 40 per cent of capacity the weights on the two sides of the drum are equal and the motor has no load except to accelerate the masses and to overcome friction. It might seem that under this condition the motor hasn't much to do, but both theory and practise show that the condition with exact counterbalancing is little different from an unbalanced load in so far as the heating of the motor is concerned. Every time the machine is started the motor must transfer energy from the electric lines to the moving parts and then reabsorb this kinetic energy in connection with the brakes when the machine slows down to stop. During rush hours when stops are being made at nearly every floor this creation and destruction of kinetic energy becomes a dominating factor in the load and consequently in the design of the machine. The energy relations involved in the accelerating and retarding of an induction motor with a pure inertia load are easily derived.

The mechanical power output of the rotor is given by

$$\text{mechanical power output} = K\,\omega\,T$$

Where $\omega$ and $T$ are the angular velocity and the torque respectively and $K$ is a constant depending upon the system of units. From elementary induction-motor theory the electrical power input to the rotor is given by

$$\text{Electrical power input} = K\,\Omega\,T$$

Where $\Omega$ is the angular velocity at synchronous speed. Since the load is inertia only

$$T = \frac{I}{g}\,\frac{d\,\omega}{d\,t}$$

Where $I$ is the *equivalent* moment of inertia of the rotor and is determined by transferring all of the kinetic energy of the moving parts of both motor and connected load to the rotor. The *energy* relations for the rotor during change of speed may then be set up as

$$\text{Mechanical energy output} = \frac{K\,I}{g}\int_{t_1}^{t_2}\omega\,\frac{d\,\omega}{d\,t}\,d\,t$$

$$= \frac{K\,I}{2\,g}\,(\omega_2^2 - \omega_1^2) \qquad (1)$$

$$\text{Electrical energy input} = \frac{K\,I\,\Omega}{g}\int_{t_1}^{t_2}\frac{d\,\omega}{d\,t}\,d\,t$$

$$= \frac{K\,I\,\Omega}{g}\,(\omega_2 - \omega_1) \qquad (2)$$

The expression (1) simply states that the mechanical output of the rotor during change of speed is equal to the change of kinetic energy. The above expressions are general. Their significance will become clear if certain special cases are considered.

### ROTOR EFFICIENCY DURING ACCELERATION

If an induction motor comes up to synchronous speed from standstill

$$\omega_1 = 0 \qquad \omega_2 = \Omega$$

$$\text{In this case rotor output} = \frac{K\,I\,\Omega^2}{2\,g} \qquad (3)$$

$$\text{rotor input} = \frac{K\,I\,\Omega^2}{g} \qquad (4)$$

It is thus seen that

$$\text{Rotor loss} = \text{kinetic energy}$$

This relation is true whatever the rotor or stator resistance and whatever the flux density. Indeed all of these quantities may be variables during the process of acceleration.

### ROTOR EFFICIENCY DURING RETARDATION

In elevator operation the process of retardation from high speed consists of throwing over to the low-speed winding. The low-speed winding is then running above synchronous speed and will act as a generator. It will transfer some of the kinetic energy of rotation back to the line. Reference to the curves in Figs. 2 and 3 will show the situation. With the high speed in operation the elevator with pure inertia load is operating at point *A*. After the shift to low speed it is operating at *B* and the rotor is subjected to retarding torque. The rotor is retarded until it is in low-speed synchronism at *C*.

The energy relations for this process may be derived from expressions (**1**) and (**2**) in which is substituted the new synchronous speed $\Omega/Z$. Also

$$\omega_2 = \Omega/Z \text{ and } \omega_1 = \Omega$$

Substituting in (**1**) and (**2**) there results

$$\text{rotor mechanical output} = \frac{K\,I}{2\,g}\left(\frac{\Omega^2}{Z^2} - \Omega^2\right)$$

$$= -\frac{K\,I}{2\,g}\,\Omega^2\left(\frac{Z^2-1}{Z^2}\right) \qquad (5)$$

$$\text{rotor electrical input} = \frac{K\,I}{g}\;\frac{\Omega}{Z}\left(\frac{\Omega}{Z} - \Omega\right)$$

$$= -\frac{K\,I}{g}\,\Omega^2\left(\frac{Z-1}{Z^2}\right) \qquad (6)$$

The negative signs show that the machine is now a generator with mechanical input, derived from the change in kinetic energy and electric output from the rotor to the stator.

If the rotor electrical output $\frac{K\,I}{g}\,\Omega^2\,\frac{Z-1}{Z^2}$ be divided by the high-speed kinetic energy from expression (**3**) there will result an expression showing the portion of the high-speed kinetic energy which is returned to the stator by regenerative braking. This expression is

$$\frac{\text{energy returned}}{\text{high-speed kinetic energy}} = 2\left(\frac{Z-1}{Z^2}\right) \qquad (7)$$

It is now possible to make up a table showing what becomes of the kinetic energy of the rotor and load when a shift is made to low speed and when after low-speed synchronism is reached mechanical brakes are applied. The unit of energy is the kinetic energy at high-speed synchronism.

TABLE I

| | | | | |
|---|---|---|---|---|
| Z (speed ratio) | 2 | 3 | 4 | 6 |
| Original kinetic energy | 1 | 1 | 1 | 1 |
| Portion returned to stator from (7) | 0.5 | 0.44 | 0.37 | 0.28 |
| Portion lost in mechanical brake | 0.25 | 0.11 | 0.06 | 0.03 |
| Portion lost in rotor winding | 0.25 | 0.45 | 0.57 | 0.69 |
| Rotor loss per cycle | 1.25 | 1.45 | 1.57 | 1.69 |

The last line shows the units of energy going into rotor loss for one complete cycle consisting of starting on high speed, changing to low speed, and applying a brake. If the mechanical brakes be applied and the winding disconnected before low-speed synchronism is reached, they will absorb a disproportionate amount of energy and the portions returned to the stator and lost in the rotor will be reduced.

## STATOR LOSSES

So far, emphasis has been laid upon rotor loss and little has been said concerning stator losses. The reason for this is that with a high-resistance rotor most of the power loss is in the rotor. Once the rotor loss is known for inertia loads the stator loss is not difficult to determine since

$$\frac{\text{Stator loss}}{\text{Rotor loss}} = \frac{\text{stator resistance}}{\text{rotor resistance}}$$

where the rotor resistance is the value after being transformed to the stator.

This relation holds true for any induction motor which has stator resistance and reactance low enough that the total currents in the rotor and stator are substantially equal and opposite. This condition is true for the high-speed winding and also for low-speed windings providing their speed is not too low. The above expression shows the advantage to the stator of the high-resistance rotor in the matter of stator loss on inertia load. The rotor loss is constant no matter what the rotor or stator resistance or the manner of applying voltage to the machine terminals. A high-resistance rotor reduces the stator loss. It is evident that the insertion of resistance in the stator leads for purposes of control has no effect upon the relation given above. The only effect is to spread the change in speed out over a greater time and to incur additional losses in the control resistance.

For those low-speed windings where stator resistances cause the performance to depart from classical circle-diagram performance (roughly below 300 rev. per min. at 60 cycles) energy loss in low-speed stator winding can be easily determined by multiplying the power loss of the stator when running idle by the time the low speed is in operation during each cycle. This is possible because the low-speed current does not vary much over the range of speed involved.

It is thus seen that with the exception noted above, the kinetic energy stored in the load is a measure of the heat developed in both the rotor and stator windings for inertia loads.

As an example of the importance of the load imposed by starting and stopping in comparison with running, consider the case of a certain motor. It is a 6-1 speed ratio and when the rotor is up to speed it alone has 15,200 ft.-lb. of kinetic energy. Couplings and brake drums revolving at the same speed will add possibly 4000 ft.-lb. The cage, with load, and counterweights may add 5000 ft.-lb. more. The total kinetic energy is then 24,200 ft.-lb. Since this is a 6-1 motor the energy transformed into heat in the rotor for a single start and stop will be

$$1.69 \times 24{,}200 = 40{,}500 \text{ ft.-lb.}$$

With capacity load the rotor has an output of 27 hp. and the slip is 16.6 per cent. With this capacity load the motor must run 13.5 sec. on high speed to have an energy loss in the rotor equal to the loss from starting and stopping. At 450 ft. per min. this would mean seven floors of high-speed running; this would mean nine floors between stops. When it is considered that with heavy loads frequent stopping is necessary it is evident that the starting and stopping develop most of the heat in the machine. Since the kinetic energy is a measure of the heat loss in the elevator motor, it is advantageous to keep the kinetic energy as low as possible in order to keep the motor temperature down. Most of the kinetic energy is stored in the rotor of the motor and those parts of the elevator machine which are directly connected to the motor shaft. The energy storage in the more slowly moving parts and in the elevator cage and counterweight are seldom, if ever, greater than 20 per cent of the total, so the rotor and next adjacent parts store about 80 per cent of the kinetic energy.

Quite obviously, then, the rotor and associated parts should have the smallest moment of inertia possible consistent with good design. The rotor lamination should be stacked on a spider to eliminate the weight of lamination that would otherwise run to the shaft. The spider itself can be designed to make a not inconsiderable saving in weight. Welded steel spiders which, in one case, weigh 43 lb. apiece displaced cast iron spiders which weighed 89 lb. apiece. The magnetic circuit and electrical circuits of the rotor should be worked at higher densities of flux and current than is permissible in continuous duty industrial motors in order to keep the mass of the rotor down to low values. In this connection, the elevator builder has his part to do in keeping down inertia losses. He should reduce as much as possible the weight of all moving parts particularly those working at the higher speeds.

The problem of dissipating the heat evolved in the motor is accentuated by the fact that the ventilation is materially cut down owing to the accelerating and retarding features of the service which keep the average speed of the motor at less than one-half of the high speed. It is necessary, therefore, to provide special means for transferring the heat developed to the ventilating air. To this end the areas of all air passages through the machine should be four or five times greater than for standard motors. This has been made possible to large extent by using arc welded steel instead of cast iron for frames. Extra large blower paddles are provided on the rotor to increase the volume of air moved as well as to conduct the heat from the rotor to the air stream. Since most of the heat in the machine is developed in the high-resistance rotor it is important to abstract as much as possible from the rotor without requiring it to cross the air-gap and heat the stator. The stator is provided with ventilating fins which are in the path of the air issuing from the motor. The circumferential fin is set into the stator lamination and draws heat from deep in the laminations. The cross fins span all the laminations and are arc welded in place. See Fig. 1.

The problem of heat dissipation increases rapidly with increase in diameter of the rotor. If we consider comparative designs at the same speed and lamination length we find for the ordinary motor that to a first approximation the various constants vary with the diameter $D$ as listed.

| Torque | Running loss | Moment of inertia | Starting and stopping loss |
|---|---|---|---|
| $D^2$ | $D^2$ | $D^4$ | $D^4$ |

The reason that the moment of inertia varies as the fourth power of the diameter is that the radial depth of the rotor lamination must vary as the diameter. This condition shows that as the diameters of elevator motors are increased in order to get more torque the heating problem due to inertia load gets rapidly more acute—and means for cooling the machine will become a constantly increasing problem.

These motors bear a horsepower rating but this rating is an empirical expression only. The horsepower is generally calculated by assuming the motor to be running at 90 per cent of synchronous speed and developing 40 per cent of the starting torque. A more useful rating is the starting torque in foot-pounds as a torque calculation is more simple and direct than a power calculation. The starting torques available in standard motors range from 10 to 2800 ft.-lb. with empirical horsepower ratings ranging from 1 to 150 hp.

## NOISE ELIMINATION

Noise elimination is of paramount importance in elevator motors. The magnetic hum so characteristic of ordinary induction motors becomes an insidious nuisance in a location where people must live with it. Hotels, apartments, offices, and hospitals demand noiseless operation. The predominant cause of noise in induction motors is the existence of harmonics of both flux and current. Elementary induction motor theory assumes that there is a single sinusoidal field rotating at synchronous speed. It is, however, well known that if the actual distributions of conductors and currents are analyzed according to Fourier's method the field is really composed of a multitude of harmonic fields rotating some forward and some backward. These fields are fairly well damped out by the rotor bars but the damping process requires harmonic currents in the rotor. The interaction of these currents and fields sets up periodic forces which in turn move the rods and teeth enough to produce noise. Pitch or coil span is known to have a vital connection with the production of harmonics and since the 5th and 7th tend to have the greatest magnitudes it is well to keep them as low as possible. This can be done by making the pitch or span equal to approximately 5/6 of a pole pitch. The number of slots per phase per pole is closely connected with the production of harmonics. Here again Fourier's analysis shows considerable improvement in this regard of a motor having two slots per phase per pole over one having a single slot per phase per pole. For this reason one should set two slots per phase per pole as the absolute minimum if one is to have a quiet motor. It is common in general motor practise to use fractional number of slots per phase per pole. This is inadmissible in an elevator motor because the resulting dissymetry produces noise from the harmonics set up.

The requirement of a minimum of 2 slots per pole per phase results in stators with a greater number of slots than is common for the ordinary induction motor of equivalent size. If we consider a 900-150 rev. per min. motor for three-phase and 60 cycles we see that the low speed has 48 poles. This means that the stator has 288 slots where the standard motor of the same size and of course of higher speed, has only 96 slots.

Another persistent source of noise is in slot combinations as between rotor and stator. Every designer of induction motors has had noise troubles from this source which were corrected by changing the number of rotor bars. In this connection it was formerly the custom to select the number of rotor bars by some empirical rule but of late this method has been partially displaced by a more rational and analytical process—having to do with the harmonics set up by the rotor bars. In spite of this advance into less empirical methods this field is by no means conquered and it offers a fertile field for further investigation and report.

## ROTOR SKEW

An interesting problem arose in connection with the skewing of the rotor rods. It is common practise among all manufacturers to skew rotors. This has two effects which it is desired to utilize. The first and most important is that with a properly skewed rotor there are no positions of the rotor where it tends to remain locked in position due to the variation in magnetic reluctance of the air-gap as the rotor is turned. This effect, sometimes known as "cogging", produces pulsations in torque if allowed to become of too great magnitude by improper amount of skew. A second effect desired from rotor skew is to reduce noise resulting from the pulsating torque. Then a third effect forced itself into the problem of design.

It happened that sometimes motors supposed to be identical in every respect showed variations in starting torque much too large to be accounted for by the ordinary variations usually encountered in building induction motors. This occurred for the most part on 48-pole windings. It was found to be due to the variations in skew of the rotor rods. As an example consider a 48-pole stator and a rotor with 90 skewed bars. The design would probably call for a skew of one rotor slot pitch. This skew is

$$\frac{48 \times 180 \text{ deg.}}{90} = 96 \text{ deg. (electrical)}$$

The effect is the same as that due to the distribution of a phase group in the stator over a plurality of slots except here the distribution is *continuous* instead of discontinuous as in the stator. To carry the comparison further consider the voltages generated in the stator and skewed rotor by a sinusoidal rotating magnetic field. In the stator if there are two slots per phase per pole each phase voltage generated in the stator consists of two components separated by an angle which is 30 deg. for three-phase and 45 deg. for two-phase. (See Fig. 4.)

$$\text{The distribution factor} = \frac{E_2}{2\,E_1}$$

The distribution factor may be defined as the actual voltage generated divided by the voltage that would be generated if the winding were concentrated.

In the case of skewed rotor rods it will be seen that each elementary length of rotor rod has an infinitesimal voltage generated in it which is out of phase with that generated in the next adjoining element. The voltage generated in the rod is the integrated voltage of these elementary lengths. Vectorially we have the elementary voltages forming the arc of a circle and the sum is the chord. Hence, the voltage actually generated in a rotor rod is less than would be generated if the rod were without skew.

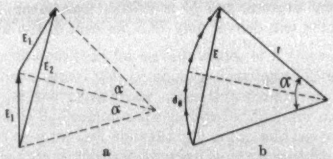

FIG. 4—VOLTAGES IN STATOR AND SKEWED ROTOR

a. Stator voltages, showing effect of distributing the winding in two slots per phase per pole. $E_1$ = voltage in ½ of 1 phase. $E_2$ = phase voltage. This effect is similar to the effect got in the squirrel-cage rotor by skewing the rotor bars.

b. Rotor voltages. With a skewed rotor bar the elemental lengths of the bars have infinitesimal voltages generated in them which are *out of phase* just the same as the voltages induced in adjacent slots of the stator are out of phase. The elemental vector voltages plotted end-on-end lie along the arc of a circle. The sum is the chord.

$$\text{"Skew factor"} = \frac{E}{\int_{\alpha=0}^{\alpha=\alpha} d\,e} = \frac{2\,r\,\text{Sin}\frac{\alpha}{2}}{r\,\alpha} = \frac{2\,\text{Sin}\,\frac{\alpha}{2}}{\alpha}$$

$$\text{The ratio } \frac{\text{actual voltage generated per rod}}{\text{voltage for unskewed rod}} \text{ might be}$$

called "skew factor."

It will be obvious that this ratio is independent of the slip and the result is that the torque is

$$\text{Torque with skew} = S^2 \times \text{torque without skew}$$

since the torque is measured by the rotor input and the rotor input varies as the square of the rotor voltage at any particular slip. An alternative way of satisfying oneself of the square relation expressed above is to consider that since the voltage induced in a skewed rod is $S$ times the voltage for an unskewed rod the current for skewed and unskewed rods will be in the same ratio. Now the current flowing in a skewed rod placed in an unskewed magnetic field will have elemental torques out of phase in the same manner that the voltages were out of phase. Fig. 4 can be used to illustrate the integration of elementary torques. Hence, the factor $S$ enters a second time.

In Fig. 5 the skew factor $S$ is plotted against skew in electrical degrees. The square of $S$ is also plotted. When we refer to the latter curve we can see the importance not only of using this skew factor in our calculations, but also the importance of keeping variations of skew in practical manufacture down to certain narrow limits. As an example, suppose a rotor has 90 rods and is 20 in. in diameter. If it is operating in a 48-pole field with a skew of exactly one slot pitch we find the 100 per cent skew to be 0.70 in., the skew angle is 96 electrical degrees, and $S^2$ is 0.785. This means that the motor will deliver only 78.5 per cent of the torque it would deliver if it were designed without skew. The effect of inaccurate skew can be shown in tabular form where "per cent skew" means the percentage of 1 slot skew.

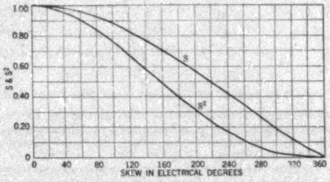

FIG. 5—SKEW FACTOR PLOTTED AGAINST SKEW

$$\text{"Skew factor" } S = \frac{360 \text{ Sin } \frac{\alpha}{2}}{\pi\,\alpha} \quad \text{where } \alpha \text{ is skew in electrical degrees}$$

| Per cent skew | Inches skew | Skew angle | $S^2$ |
|---|---|---|---|
| 80 per cent | 0.56 | 77 deg. | 0.82 |
| 100 per cent | 0.70 | 96 deg. | 0.785 |
| 120 per cent | 0.84 | 115 deg. | 0.71 |

Thus, we see if the skew is held only approximately that the torque of the machine may vary by

$$\frac{0.82 - 0.71}{0.785} = 14 \text{ per cent}$$

This variation is too large to be neglected.

## STATOR COPPER BALANCE

In the case of a two-speed motor with two separate windings the question of the proper balance of copper section between the two windings is of utmost importance. If this is not carefully attended to it will be found that out on the job one winding will be running hot while the other is cool. It is obvious that the proper division of slot area between the two windings depends upon the duty cycle of the elevator and the relative service demanded from the two windings. A little calculation of the losses in the two windings will show that the minimum amount of heat will be evolved in the stator windings when the ratio of the copper cross-sections of the two windings is equal to the ratio of energy (not power) losses in the two windings. That is,

$$\frac{A_1}{A_2} = \frac{Q_1}{Q_2}$$

Where $A$ and $Q$ represent the cross-sectional area of copper in the slot and the energy losses respectively and the subscripts identify the winding with which the particular quantity is associated.

While there are two stator windings there is only one rotor winding and it is necessary to build this rotor winding so that it will have the correct resistance for both speeds. The losses in the rotor winding occur in two parts of the circuit—in the bars and in the end rings. The ratio of these losses is given by the expression

$$\frac{\text{Ring loss}}{\text{Bar loss}} = \left(\frac{0.635\,N}{P^2}\right) \times \left(\frac{D}{L}\right) \times \left(\frac{A_B}{A_R}\right) \times (K)$$

Where $P$ Number of poles
$N$ Number of rotor bars
$L$ Length of rotor bar
$D$ Mean diameter of end ring
$A_R$ Cross-sectional area of the end ring
$A_B$ Cross-sectional area of one bar
$K$ Ratio of conductivities of material in bar and material in ring (Unity for bar and ring of same material)

This expression shows that in a two-speed motor with a speed ratio of 6–1 the proportion of ring loss to bar loss on the low speed is 1/36 of its value on the high speed.

In one such rotor the ratio of ring loss to bar loss is 0.292 for the high-speed condition. On the low speed this ratio falls to 0.008. In this case the ring loss is negligible on low speed. It is then obvious in this case that the proper method of getting the desired rotor resistance on both speeds is to design the rods for low-speed operation and design the rings to go with these rods for proper high-speed design.

## TRANSFORMER EFFECTS IN TWO-SPEED STATORS

The design of the stator winding in a two-speed two-winding motor is subjected to limitations which are not present in a single winding motor because of the transformer effects between the windings. When one winding is in operation the revolving flux cuts the conductors of the other winding and sets up voltages in them. Great care must be taken that these induced transformer voltages do not set up parasitic currents in the idle winding and give trouble due to overheating and noise. In certain speed combinations, even though internal parasitic currents are eliminated, voltages appear at the terminals of the idle winding which may cause trouble with connected control apparatus.

When one winding is operating it is obvious that every conductor in the idle winding has the same e. m. f. induced in it as is induced in a conductor of the operating winding. The problem is to so connect each winding that these e. m. fs. either cancel each other out or at least do not set up parasitic currents when the windings are out of use and at the same time to so connect them that the operation will be proper when in use.

A full account of the analysis necessary to cover the subject of elimination of harmful transformer effects is long enough to form a paper in itself so the present paper will limit itself to brief explanations of methods, followed by tabulated results which would be obtained by extensions of the methods.

## ELIMINATION OF CIRCULATING CURRENTS IN THE HIGH-SPEED WINDING

We will first concern ourselves with transformer effects in the high-speed winding induced by operating the low-speed winding.

*Correction by High-Speed Coil Pitch.* If the speed ratio is, for instance, 2 it is evident that if the high-speed coils are wound full pitch the two conductors forming a turn will have e. m. fs. induced in them 360 deg. apart and the turn e. m. f. will be zero. If the speed ratio is 3 the turn e. m. f. will be zero if the high-speed pitch is 2/3 or 4/3. We may generalize and say if the speed ratio is $Z$ the e. m. f. per turn of the high speed will be zero if the

$$\text{high-speed pitch} = \frac{2}{Z}, \frac{4}{Z}, \frac{6}{Z} \text{ etc., where } Z \text{ is}$$

always taken $> 1$ and may be fractional or integral. By using this pitch, the high-speed winding may then be connected any way desired without further thought to transformer effects in it. The designer, however, may not wish to use the coil pitch demanded by this type of correction because it may be a pitch conducive to noise from harmonics or it may be a pitch not physically attainable with the number of slots at his disposal. He must then accept turn voltages other than zero and expect to annul them in coil or group connections.

*Correction in the Phase Group.* In case the induced voltage per turn is not zero, the voltage per coil will be the turn voltage multiplied by the number of turns. The coils which make up a phase group are equally distributed over 60 electrical deg. in an ordinary three-phase winding. When the low speed is operating this 60 deg. is changed to 60 $\times Z$ deg. This condition can be very simply shown by vectors in Fig. 6. The vectors $A$, $B$, and $C$ represent the voltages induced in adjacent high-speed coils of the same phase group when the high speed is operating. These coils are always connected in series so that the group voltage is the vectorial sum. When the low speed is operating the span that was 60 deg. now becomes 60 deg. $\times Z$ because the electrical degrees between adjacent coils is $Z$ times what it was before. This vectorial condition is shown in Fig. 7.

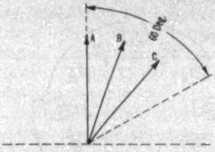

FIG. 6—VOLTAGES INDUCED IN HIGH-SPEED WINDING WHEN HIGH-SPEED WINDING IS OPERATING

In a three-phase high-speed winding the voltages $A$, $B$, $C$ generated in the various slots of a phase group are spread over 60 electrical degrees *only* when the high speed is in operation. When the low speed is operating these vector voltages are spread over 60 $\times Z$ deg.

It is obvious that for certain values of $Z$ the vectors in a phase group will be equally distributed over 360 deg. In the three-phase case this condition occurs when $Z = 6$, a common speed ratio for elevator motors. In this case the coil voltages in a group add up to zero and the groups may be connected in any desired manner without reference to transformer effects. By extension of this reasoning we may summarize on corrections in the phase group.

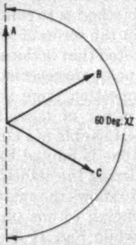

FIG. 7—VOLTAGES INDUCED IN HIGH-SPEED WINDING WHEN LOW-SPEED WINDING IS OPERATING

The vector voltages generated in a high-speed group are spread over 60 $\times Z$ electrical degrees when the low speed is operating. The transformer voltage in a high-speed group is then $A + B + C$. In case 60 deg. $\times Z$ is a multiple of 360 deg., $A + B + C = 0$.

Group voltages on the high speed will be zero for
3 phase (60 deg. distribution) when $Z = 6$, 12, or any multiple of 6
3 phase (120 deg. distribution) when $Z = 3$, 6, or any multiple of 3
2 phase when $Z = 2$, 4, or any multiple of 2

*Correction by Group Connections.* There occur many cases in two speed-windings where neither the turn voltage nor the group voltage can be made zero, the latter for those speed ratios which do not occur in the above table. In those cases where one has a group transformer voltage in the high-speed winding with low-speed operating one must be careful that any internal parallel connections are not the seat of parasitic circulating currents due to these group voltages. Suppose one has a three-phase motor with four poles on the high speed and 16 on the low speed in which the turn voltage has not been made zero by correction in coil pitch. There will then be transformer voltages in the 12-phase groups. Suppose the designer wishes to connect the four groups of a phase two series two parallel. There are two common ways of making this connection in single-speed motors—one is to connect the corresponding groups from adjacent poles in series and then parallel two such series of adjacent poles as in Fig. 8. The other method is to connect alternate poles in series and parallel the series of alternate poles as in Fig. 9. It is to be noted that in the adjacent connection the even numbered poles are reversed in the series while in the alternate connection there is no reversal inside the series. While either of these series-parallel connections would be permissible in a single-speed winding, it will be seen that one is limited to the adjacent connection when considering the transformer effect from a 16-pole field. Fig. 10 shows the arrangement of the four group voltages belonging to one phase when the high speed is operating while Fig. 11 shows the new array of vectors when the low-speed flux acts upon the high-speed winding. The angular distance between adjacent vectors has been increased from 180 deg. to 4 × 180 deg. because 4 is the speed ratio.

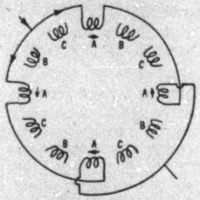

FIG. 8—STATOR CONNECTED SERIES-PARALLEL WITH ADJACENT POLES IN SERIES

Note that adjacent poles are reversed

The adjacent connection gives 1 − 2 in series in one leg of the parallel connection with 3 − 4 in the other. Here we see that 1 − 2 has zero transformer voltage as has also 3 − 4. There will then be no trouble with circulating currents between the two legs of the parallel connection. On the other hand, the alternate connection shows 1 + 3 paralleled with − 2 − 4. The vector arrangement with transformer voltages is shown in Fig. 12. This connection causes all the transformer voltages to add up in phase around the local parallel circuit and the circulating current will make the connection impossible.

Extending this analysis a table is now given which shows the number of poles which must be in series to make transformer voltage zero in a series leg and thus eliminate circulating currents in the high-speed winding with the low-speed operating.

TABLE II

| Z | Adjacent connection | Alternate connection | |
|---|---|---|---|
| 2, 4, 6, etc. | 2 | Impossible | Number of poles in series must be a multiple of number shown to eliminate transformer voltages in series leg of parallel connection. |
| 3/2, 5/2, 7/2 etc. | 4 | 2 | |
| 4/3, 8/3, 10/3 etc. | 6 | 3 | |
| 5/3, 7/3, 11/3 etc. | 3 | 3 | |
| 5/4, 7/4, 9/4 etc. | 8 | 4 | |
| 6/5, 8/5, 12/5 etc. | 10 | 5 | |
| 7/5, 9/5, 11/5 etc. | 5 | 5 | |

It will be noted that the foregoing tabulation does not contain any speed ratios where *Z* is an odd number. The reason for this is that if the speed ratio is an odd number, it is impossible to connect the series circuits so that the voltage in a series leg is zero. It will be found, however, that with odd speed ratios the coils in the high-speed winding may be connected in any standard manner because it will always occur that the transformer voltage in one leg of a parallel connection is equal to the transformer voltage in the other leg (or legs) of that same phase and thus no circulating current will flow. (See Fig. 13.) This does mean, however, that there is a transformer voltage generated in each phase which voltage appears at the terminals of the machine. This fact may have a vital bearing on the type of control used with the motor.

## ELIMINATION OF CIRCULATING CURRENTS IN LOW-SPEED WINDING

A little thought will show that it is impossible to annul the transformer voltage in the low-speed winding by the first two devices used in the high-speed winding, that is, by choosing a particular coil pitch or by having the voltages in a group add to zero. The only recourse in eliminating trouble in the low-speed winding is to make sure that circulating currents cannot occur in any parallels by so connecting the proper poles in series that

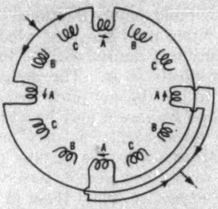

FIG. 9—STATOR CONNECTED SERIES-PARALLEL WITH ALTERNATE POLES IN SERIES

the transformer voltage of a series leg is made zero just as was done in the high-speed winding. The following table will show the proper number of poles to be connected in series to obtain zero leg voltage for the various speed ratios and the two commonest type of connection, that is, adjacent poles in series and alternate poles in series.

TABLE III

| *Z* | Adjacent connection | Alternate connection | |
|---|---|---|---|
| 2 | 4 | 2 | Number of poles in series must be a multiple of number shown to eliminate transformer voltages in series leg of parallel connection. |
| 3 | 3 | 3 | |
| 3/2 | 6 | 3 | |
| 4, 4/3 | 8 | 4 | |
| 5, 5/3 | 5 | 5 | |
| 5/2, 5/4 | 10 | 5 | |
| 6, 6/5 | 12 | 6 | |
| 7, 7/3, 7/5 | 7 | 7 | |
| 7/2, 7/4, 7/6 | 14 | 7 | |

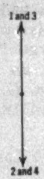

FIG. 10

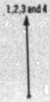

FIG. 11

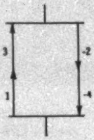

FIG. 12

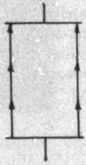

FIG. 13

FIG. 10—GROUP VOLTAGES IN HIGH-SPEED WINDING WHEN HIGH-SPEED WINDING IS OPERATING

These are the four group voltage in one-phase of a four-pole stator. The distance between successive voltages is 180 electrical degrees.

FIG. 11—GROUP VOLTAGES IN HIGH-SPEED WINDING WHEN LOW-SPEED WINDING IS OPERATING

When the high-speed winding of Fig. 10 is subjected to the low-speed field of 16 poles the successive polar voltages are 4 × 180 deg. apart because 4 is the speed ratio

FIG. 12—LOCAL CIRCULATING CURRENTS SET UP IN HIGH-SPEED WINDING WITH SERIES-PARALLEL CONNECTION

These currents are induced by transformer effects from the low-speed winding

FIG. 13—TRANSFORMER VOLTAGES SET UP IN HIGH-SPEED WINDING WHEN THE SPEED RATIO IS AN ODD INTEGER

No circulating currents can occur but induced transformer voltages do appear at the terminals of the high-speed winding

As an example of the use of these tables, suppose it is wished to build a 3-phase motor with synchronous speeds of 900 and 225 rev. per min. This is a 4 – 1 ratio. There will be 8 and 32 poles. If there are 192 slots there will be 24 slots per pole on the high speed and 6 on the low speed.

Transformer voltage in the high speed may be eliminated at the start by making the pitch $P = Z/4$ which in this case is $P = 1$ since $Z = 4$. But, it may not be desired to wind this high speed with full pitch due to harmonics or due to the fact that the designer desires a shorter pitch to obtain the proper flux density. He will then have transformer voltages in the coils. He will also have transformer voltages in the groups and the question remains how to connect the groups to obtain zero leg voltage. Table II shows that if he connects adjacent poles in series only two poles to a series leg are needed although any multiple of two may be used. He may then connect the high-speed groups

| | |
|---|---|
| 2 series | 4 parallel |
| 4 series | 2 parallel |
| 8 series | |

He also sees that no parallel connection is possible if he connects alternate groups in series.

Turning now to the low-speed winding, he sees the limitations from Table III. This table tells that circulating currents in parallels will be eliminated if he has multiples of eight poles in series with the adjacent connection and multiples of four poles in series with the alternate connection. We may then connect the 32 poles as follows:

| Adjacent Connection | | Alternate Connection | |
|---|---|---|---|
| 8 series | 4 parallel | 4 series | 8 parallel |
| 16 series | 2 parallel | 8 series | 4 parallel |
| 32 series | | 16 series | 2 parallel |
| | | 32 series | |

## CONCLUSION

The growing demand for and use of a-c. elevators is natural since d-c. is more expensive to produce and distribute than a-c. In case a-c. only is available in a given locality it is necessary to install conversion apparatus in addition to the elevators in order to operate d-c. elevators. There is every indication that the use of a-c. elevators is in its infancy. As the use is extended the design problems and their solutions which are the subject of this paper will represent, it is hoped, a substantial start in the more economical use of electric power and invested capital in this particular field.

# Electric Welding of Pipe Lines

BY J. D. WRIGHT[1]
Associate, A. I. E. E.

*Synopsis.—This paper outlines the process of manufacture of steel pipe from flat rolled steel plates by automatic metallic arc welding. Data are given showing the physical and chemical analysis of the plate, the weld, and the welding wire, as well as the speed of welding and electrode and power consumption.*

* * * * *

THE economies which have been effected in many manufacturing operations during the past few years by the adoption of electric arc welding for manufacturing as well as for tool repair have been so outstanding as to command the attention of all industries.

In many cases, the reduction in cost has been accompanied by a distinct improvement in quality, so that in these days of increasingly keen competition, no manufacturer marketing a product in which fabricated metal parts are, or might be used, should fail to make a thorough study of the possibilities of electric welding.

One of the newer applications of automatic arc welding is in the fabrication of pipe from flat rolled steel plates. It is particularly applicable to the larger sizes of steel pipe which heretofore have been made either by riveting, by the lock-bar process, or by the hammer weld process. The interest aroused by several successful installations of lines of pipe fabricated by the electric arc welding process has been very widespread, and it is the purpose of this paper to discuss the present state of the art as exemplified by a recent installation.

The example selected is the process employed for fabricating the pipe for a line approximately eight miles long, to convey water from the Provin Mountain Reservoir to the City of Springfield, Massachusetts. From the reservoir to the west bank of the Connecticut River, a single line of 54-in. and 48-in. diameter pipe is used. Two lines of 36-in. diameter each are laid under the Connecticut River, and from its east bank a single line of 48-in. and 42-in. pipe connects with the present distribution system of the City of Springfield. The thickness of the plate used in the pipe varies from 5/16 to 1/2 in.

## TESTS OF WELDED JOINTS

Before bids on welded pipe were submitted, tests were made to determine the strength of the welded joint and a definite procedure was worked out to insure thoroughly reliable and uniform results.

The plates used for the tests were of fire-box steel with tensile strength between the limits of 52,000 and 62,000 lb. per sq. in., as specified by the Engineer of the Board of Water Commissioners. The following shows typical analysis and physical properties of the plate steel:

| | | | |
|---|---|---|---|
| Carbon...... | 0.20 per cent | Yield point— | 35,450 lb. per sq. in. |
| Manganese... | 0.40 | Tensile strength | 57,500 lb. per sq. in. |
| Phosphorus .. | 0.015 | Per cent elongation | 31.5 |
| Sulphur...... | 0.029 | Per cent reduction of area | 56.3 |

Sections 3 in. wide by 48 in. long were sheared from ½-in. plate, and the sections beveled on one 48-in. side as shown by Fig. 1. Two sections were then welded together using the multiple arc process. This will be described in greater detail later. Two beads were deposited, the first with 3/16 in. G. E. type "F" welding electrode using 300/320 amperes at an arc voltage of 18/22, and the second with 3/16 in. G. E. type "B" electrode using 320/360 amperes and 18/22 volts. The welding was done at a speed of approximately 4½ in. per minute.

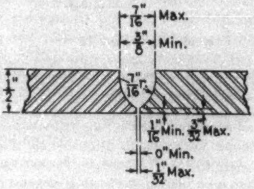

FIG. 1—DIMENSIONS OF BEVEL FOR WELDING ½-IN. PLATES

The following table shows chemical analysis of the two welding electrodes:

| | G. E. type "B" | G. E. type "F" |
|---|---|---|
| Carbon...................... | 0.10 max. | 0.13/0.18 |
| Manganese.................. | 0.25/0.45 | 0.40/0.60 |
| Sulphur...................... | 0.045 max. | 0.03 max. |
| Phosphorus.................. | 0.03 max. | 0.45 max. |
| Silicon...................... | Trace | Trace |

Type "F" is a solid wire to which a special treatment is given to insure a uniform flowing quality. Type "B" has a center metallic core surrounded by a layer of flux, the whole being incased in a metallic sheath.

The welded plates were cut into strips 1½ in. wide and tested for tensile strength in a standard testing machine. The following results are typical of many specimens:

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[1] Industrial Engineering Dept., General Electric Company, Schenectady, N. Y.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

| Specimen | Tensile strength lb. per sq. in. | Failure |
|---|---|---|
| 1 | 56,700 | Weld |
| 2 | 61,700 | Weld |
| 3 | 60,200 | Steel |
| 4 | 61,870 | Steel |
| 5 | 55,700 | Weld |
| 6 | 60,600 | Steel |

Other specimens were subjected to various bend tests to check the ductility of the weld.

Fig. 2 shows very clearly the metal deposited by the first and second arcs and the zone in the plate stock into which the heat of the weld has penetrated. Photomicrographic studies of the grain structure of the steel in the weld and adjoining plate show total lack of a definite line marking the transition from the weld to the plate, and no evidence whatever of any injury to the plate, owing to heat of the weld.

FIG. 2—DEEPLY ETCHED SECTION OF MULTIPLE ARC WELDED ½-IN. PLATE

FIG. 3—36-FT. PLATE PLANER WITH TWO PLATES IN POSITION FOR MACHINING BEVEL ON 30-FT. SIDE

## MANUFACTURE OF PIPE

The pipe for the Springfield water line is made in 30-ft. lengths from two 30-ft. plates which are bent into half circles and automatically arc welded together. Some consideration was given to welding of the circumferential joints in the field, but because of considerable opposition, it was decided not to do this on this particular job, and the 30-ft. sections are riveted together. To provide for this the plates are sheared so that the pipe diameter increases slightly from one end to the other, thereby permitting the small end of one section to fit into the large end of the next section an amount required for the riveted joint.

FIG. 4—36-FT. BENDING ROLLS FORMING 30-FT. HALF SECTION OF 48-IN. PIPE

The first operation in the manufacture of the pipe after the flat plates have been sheared to size is to bevel the sides accurately as shown in Fig. 1. This is done simultaneously on two plates on the plate planer shown in Fig. 3. On each plate, two lines are then scribed, each parallel to the upper edge of the bevel and ¾ in. from it.

The plate is then taken to the bending rolls, (Fig. 4), and by means of a special jig, the two 30-ft. edges are bent to the proper radius. The whole plate is then formed into a true half circle. Next the two halves of the pipe are placed in a specially designed frame, (Fig. 5), and tack welded together approximately every 16 in. on the inside by hand. After the raised portions of the beads are removed by grinding, the pipe is placed in the automatic welding machine, (Fig. 6).

FIG. 5—FRAMES OF SPECIAL DESIGN SUPPORT THE TWO 30-FT. HALF SECTIONS OF 48-IN. PIPE WHEN BEING TACK WELDED BY HAND FROM THE INSIDE

## PIPE WELDING MACHINE

The pipe welding machine consists essentially of three horizontal beams, two above and one below.

Enclosed in the lower beam and extending throughout its full length are several sections of fire hose to which compressed air can be admitted. On the hose rests a series of plungers which in turn supports a "backing-bar," the latter being fitted with a flat copper chill bar approximately two inches wide. Application of compressed air causes the hose to expand, thereby raising the plungers, and the copper strip in the backing-bar is pushed up against the under side of the joint at a pressure of 200 lb. or more per running inch. The backing-bar is also provided with an insulated conductor which forms part of the return circuit for the welding current. By shunting the proper amount of current through this bar when the pipe is being welded, the magnetic disturbances of the arc can be very effectively controlled.

Fig. 6—End View of 36-Ft. Pipe Welding Machine Showing 30-Ft. Section of 48-In. Pipe Ready for Automatic Arc Welding of Longitudinal Seam

Fig. 7—36-Ft. Pipe Welding Machine Showing Two Travel Carriages Each With Two Welding Heads for Automatic Welding of Pipe by Multiple Arc Process

To the lower side of the upper beams of the machine are attached two copper jaws spaced approximately two inches apart and the pipe is placed in the machine so that the joint to be welded is located centrally between these two copper jaws and directly over the copper strip in the backing-bar.

The multiple arc welding process previously mentioned employs two arcs, one following about eight inches behind the other. The two automatic welding heads, used to feed the wire, are mounted on a single motor driven adjustable speed travel carriage, (Fig. 7), which moves the heads along the work at the proper welding speed.

When work was first started on the manufacture of the pipe for the Springfield line, only one travel carriage with two welding heads was used. This carriage, of course, traveled the full length of each 30-ft. seam. A little later, a second travel carriage with two more heads was added. Welding was then carried on simultaneously with four arcs, one carriage starting at one end and the other at about the middle of the seam. This reduced the welding time per pipe by about 50 per cent. It is expected that a third carriage with two more heads will soon be added, each pair then welding about one-third the total pipe length with corresponding reduction in welding time.

Fig. 8—48-In. Pipe, 30 Ft. Long Fabricated From Two ½-In. Plates by Automatic Arc Welding Undergoing Hydrostatic Pressure Test of 240 Lb.

After one seam is completely welded, the pneumatic clamp is released and the pipe is rotated to bring the second joint into position for welding.

## SPEED OF WELDING; ELECTRODE AND POWER CONSUMPTION

The speed of welding attained by the multiple arc process with two welding heads on ½-in. plate is about 22½ ft. per hour. Using approximately 380 amperes on the first arc and 330 amperes on the second, the total consumption of 3/16-in. electrode is from 0.8 to 0.85 lb. per foot of weld. These welding currents are somewhat different from those used when the test plates were welded, but were found to give better results on the joint between the two sections of pipe. Current for each pair of welding heads is obtained from a 1000-ampere 1-hr. rated constant potential welding generator driven by an induction motor. The power consumed is approximately 2.15 kw-hr. per foot of weld on ½-in. thick plate.

### INSPECTION AND TESTS OF WELDS

At the request of the inspector, test plates having a bevel as specified for the pipe joints are placed in the machine and welded under the same conditions as the pipe itself. These plates are then cut into specimens and tested.

The extent to which the weld is reinforced, that is, its height above the surface of the plate, is usually from 1/16 to 1/8 in. The minimum and maximum values permitted by good practise are 1/32 and 3/16 in. respectively. The weld bead must not be less than 5/8 in. nor more than 1 in. in width and must also be central within 1/16 in. between the lines scribed on the plate each side of the joint. Any holes which are seen on the top surface of the deposited metal are carefully chipped and if they extend below the surface of the plate, the spot is rewelded by hand. The edges of the bead are also examined to see that the weld metal is thoroughly fused along the top of the plate. Any cracks or hollow spots are chipped and rewelded by hand.

FIG. 9—30 FT. SECTION OF 48-IN. PIPE ABOUT TO BE LOWERED INTO ELECTRICALLY HEATED VERTICAL DIPPING TANK TO RECEIVE PROTECTIVE COATING OF COAL TAR PITCH VARNISH

FIG. 10—LAYING OF STEEL PIPE LINE FOR SPRINGFIELD, MASS., WATER SUPPLY. 30-FT. LONGITUDINAL JOINTS ARE AUTOMATICALLY ARC WELDED. CIRCUMFERENTIAL JOINTS MADE IN THE FIELD ARE RIVETED

To determine the amount of penetration, the under side of the welded joint is carefully examined. It is necessary that the metal be so thoroughly fused that no crack can be seen between the edges of the plate.

After the welded pipe has been given a careful visual inspection and any defects rewelded, it is placed in the testing machine, (Fig. 8), and subjected to the following hydrostatic pressures in pounds per square inch:

| Thickness of pipe in inches | 5/16 | 3/8 | 7/16 | 1/2 |
|---|---|---|---|---|
| 66-in. pipe | .. | 160 | .. | .. |
| 54-in. pipe | 135 | 160 | 187 | 213 |
| 48-in. pipe | .. | .. | 210 | 240 |
| 36-in. pipe | .. | .. | .. | 320 |

### DIPPING AND LAYING THE PIPE

The rivet holes are then punched in each end of the pipe after which it is thoroughly cleaned and dipped vertically in an electrically heated tank of coal tar pitch varnish, (Fig. 9). The pipe is submerged in the bath long enough to heat the metal uniformly to the temperature of the bath. It is then removed and suspended in a vertical position until the coating has drained and set.

The pipe is then ready for transporting to the field and laying in the trench, (Fig. 10). After the pipes have been properly placed and connected by temporarily bolting, the circumferential joints are riveted and caulked. The middle portion of each length of pipe is then backfilled but the field joints are left exposed until the line has been tested for tightness.

### CONCLUSION

At the time this paper was written, approximately three miles of pipe had been delivered to the field, and its installation in the trench was progressing rapidly.

The advantages gained by the electric welding of pipe as compared with other methods of manufacture are a very substantial reduction in cost and a superior finished product. The reduction in cost is secured not alone by the decreased weight of steel required but also by a reduction in the cost of the actual work of fabricating the pipe.

Owing to the smooth interior of the welded pipe as compared with the riveted pipe, the resistance to flow is decreased. The circumferential joints are made more easily with welded pipe because of uniform wall thickness whereas with riveted pipe the wall is of double thickness at the riveted joint. The joining of the ends of pipe made by the lock bar process is rendered difficult owing to the presence of the bar.

Arc welded pipe is also invading the field of lap welded pipe produced by the lap weld mills because of the fact that the thickness of the wall of the latter is fixed and often times the pressures are such that much lighter arc welded pipe can be used with consequent reduction in the cost of the line.

## Discussion

**J. F. Lincoln:** Mr. Wright's paper is extremely interesting because it brings out a second successful method for doing this sort of work by the electric arc.

The outstanding example of pipe welding up to this time is the Mokelumne River line, 90 mi. in length and containing 78,000 tons of steel. This line has been completed now for some months. This was done with the carbon-arc process instead of the metallic-arc process as is the case in this smaller line described by Mr. Wright.

It is interesting to compare the results as actually obtained in the Mokelumne River line and that described by Mr. Wright. The steel used in both cases was identical—the tests made of the specimens would show approximately the same results.

The welding speed per arc is slightly higher in the case of the Mokelumne River line by not more than 20 per cent. The cost of doing the welding is somewhat less in the case of the Mokelumne River line because of higher speed, because of cheaper filling material, and because of less power used.

In the case of the Mokelumne River line the hydrostatic tests were approximately 60 per cent higher than in the case of the line described. There was also added, in the case of the Mokelumne River line, a hammer test which is much more severe than the hydrostatic test. This hammer test was applied with a tensile stress on the metal itself in excess of 22,500 lb., and an ultimate test running up to a maximum of 28,000 lb., the tensile test in this case being nearly double that used in the line described.

There has been a good deal of progress made in the application of carbon-arc welding since the manufacture of the Mokelumne River line. Since that time the new development of the "electronic tornado" has more than doubled speeds, has eliminated practically all tendency to porosity which heretofore was present in all cases on both the carbon and metallic electrode welding of thick plate, and it has practically eliminated any necessity for repairing. Welding speeds of a single head in excess of one foot per minute on half-inch plate, and with double heads welding speeds of double that, have been obtained. The welds can be bent flat on themselves without rupture and the ductility of the weld metal is fully as great as the ductility of the plate itself.

I think it is safe to say that as far as the welding is concerned in the manufacture of pipe, all necessary development has been done. There is still much to be desired in the planing, crimping, rolling, and assembly of the plates before welding, which progress will enormously reduce manufacturing costs.

At the present time it probably is true that the cost of welding of the pipe itself is less than 1 per cent of the total cost of the pipe, so that any further progress in welding cost reduction is of little moment compared to the cost reduction possible in the operations other than welding.

**J. C. Lincoln:** The pipe described in Mr. Wright's paper has one end larger than the other so the small end will telescope into the larger end and the ends are riveted as described in the paper. I imagine the inside ends are probably flat-riveted so as to decrease the eddy that would result from the ordinary round-head rivet.

In any case there will be a very considerable eddy at the joint. The metal is $\frac{3}{8}$ or $\frac{1}{2}$ in. thick and all around the pipe there is bound to be an eddy. Mr. Day of the United States Reclamation Service was telling of difficulty which he experienced where eddies were encountered in pipe, and Mr. Imlay of the Niagara Falls Power Company says they have had the same difficulty at Niagara Falls. Where there is a severe eddy, apparently a chemical action takes place, eating out the pipe at that point. In the case Mr. Day described to me, a cast-iron pipe 2 in. thick is corroded so that it has to be replaced or repaired in the very near future.

Mr. Imlay said that on their wheels at Niagara Falls repairs of the same sort had to be made as one of the regular upkeep operations.

It seems to me that is a possible criticism of this method of joining pipe though that has nothing to do with Mr. Wright's paper. It won't be very long, I think, before pipe will be joined, not by riveting, but by welding, and if the pipe is joined by welding there will be no special trouble in making a butt weld in which the ends of the pipe will be beveled and so welded as to leave the inside of the pipe smooth and thus avoid this eddy.

**R. E. Barnard:** I am chief engineer of the Hardesty Manufacturing Company of Denver, manufacturing electric-arc-welded pipe. The particular defect in riveted pipe called to your attention by Mr. Lincoln constituted the main reason for our making electric-welded pipe instead of riveted. In order to eliminate erosive action at the joint we have for several years made a special type of slip-joint pipe in which a collar is electrically welded to one end of a constant-diameter tube and this collar forms the bell into which the spigot end of the abutting section is driven. The result is a smooth interior pipe of the slip-joint type and eliminates the particular destructive action to which reference has been made. We have just completed near Yoder, Wyoming, an electric-arc-welded line entirely field-welded. It is 72 in. in diameter, $\frac{1}{4}$ in. thick, and made with field joints butt-welded. The plates were 6 ft. long, and the field sections 12 ft. long.

The line is about 900 ft. long and has two elbows in the vertical plane, each of about seven degrees deflection. The only expansion joints in the line are at the ends where special transition sections are imbedded in the inlet and outlet.

This 72-in. pipe is made by very nearly the same process as described in the paper, except that the plate edges are not beveled. The quarter-inch plate, not beveled, is fused through with the Lincoln type of machine without difficulty. For making the longitudinal seam we use the automatically controlled and driven Lincoln arc operating over a clamp similar to the one shown in the paper, only not so large. Circumferential seams are automatically welded by the General Electric metallic arc welder operating over a revolving clamp. All shop welding is automatically done and the field joints made by hand acetylene-gas welding.

**H. J. Lawson:** We have had considerable experience on the Salt River project with welding on repairs of the electrical machinery and other machinery used in the maintenance of the power system and the irrigation system. Especially we have had considerable experience in repairing runners and water wheels on which there was pitting and erosion. Bronze runners are very easily repaired in that manner.

We took one runner out of a 7500-hp. wheel. It was pitted only slightly but we took it out because one vane in the runner was thin. It must have come from the factory that way originally. It has been in operation about 14 years before there was any necessity of thickening the vane. We took out the wheel and built up that particular vane from less than $\frac{1}{4}$ in. thick to $\frac{3}{8}$ in. and made a successful job of it. While doing that we filled up the pitted places on the back side of the vanes. We also built up by welding, the outside periphery of the wheel where the water wear had taken place, and turned it down to proper size. It was then carefully balanced, after which it was practically as good as a new runner.

In repairs of heavy equipment, excavating machines, etc., where there is excessive wear on steel pins and bearings, especially pins that are quite heavy and expensive, we found that welding saves money and gets the job done quickly.

We also have had considerable experience in welding the shafts of turbines where they have cut and grooved within the stuffing boxes. In every case where we repaired them in that manner we have had no further trouble from the part that was welded. The welding has all been done by electric arc.

**C. M. Day:** The particular problem of the Bureau of Reclamation relates to cavitation in cast-iron pipes through which water is discharged under high heads, and at high velocities, from reservoirs. At Arrowrock Dam, on the Boise Project, Idaho, we have 20 58-in. balanced valves mounted on the upstream face of the dam, with 54-in. cast-iron pipes embedded in the concrete dam, and the discharge from each valve may be 800 cu. ft. per sec., resulting in a velocity of 50 ft. per sec.

The jet of water, immediately below the valve, is smaller than the pipe, but as the pipe is completely filled within a short distance, and the water velocity is high, a vacuum exists in the unfilled space, which seems to induce a chemical action, perhaps oxidation, which destroys the metal in the cast-iron conduit. This cannot be erosion as the water is not in contact with the metal. These valves and conduits have been installed about 13 years, and at the top and bottom of the pipes, where the shell is 2 in. thick, the metal has almost disappeared in places.

Our problem is to restore the pipes to practically their original condition. We have tried cement grout and lead, but it will not last throughout one season, and arc welding seems to be the only solution. It seems impractical to remove all of the existing metal throughout the affected area by chipping it out, but it is expected to chisel out at least enough to leave perhaps 50 per cent of the area with clean metal. It is expected that each conduit will require at least 400 lb. of new metal, half of which must be deposited overhead.

It has been suggested that copper or bronze, which resists cavitation much better than steel, be used, but to date we have not found anyone who can successfully deposit these metals in a proper manner.

In a similar valve installation at Pathfinder Dam, where the conduits below the valves were lined with ⅜-in. steel plates, with the rivets countersunk on the inside, any rivet head that projected even 1/16-in. caused this cavitation along the surface of the pipe for at least 8-in. below the rivet, where the vacuum would be caused by the exceedingly high velocity of the water, and in this area the pipe shell would be gradually eaten through This action was so rapid and serious that after two or three seasons' use it was necessary to remove the plate-steel linings, and line the conduits with rich concrete grout, with 24 1.5-in. air-vent pipes embedded in the concrete lining, extending to the point where cavitation existed, to break the vacuum. This method seems to have solved the problem at Pathfinder Dam.

At Arrowrock Dam I am confronted with a large repair problem, and will be very grateful for any suggestions as to how to overcome the trouble and replace the lost metal with new metal that will make a satisfactory bond.

**J. D. Wright:** I should like to inquire why Mr. Day feels that this is a chemical action in what he describes as a vacuum. It would seem to me as though it would be an erosive action at the place where the water enters the cast-iron pipe. I don't see how it can be a chemical action in the vacuum.

**C. M. Day:** I have never seen a complete explanation. In the first place, where cavitation exists the water is at no time in contact with the metal, and for this reason it has always been assumed that the action must be chemical. Because of the conditions of installation it has been impossible to get close enough to make an investigation.

**H. J. Lawson:** At the Roosevelt Dam we have had the same trouble, that is, the pitting of the water wheels. It is commonly known that in a partial vacuum oxidation occurs very rapidly and that this action is simply an oxidation or very rapid rusting.

**J. H. McCabe:** Has there been any development in electric welding of airplane fuselage where they use drawn-steel tubing about 18 or 20 gage? A plant in Colorado Springs is using that type of construction and we have never been able to convince them that the electric arc welding may be used satisfactorily. They employ gas welding.

**J. D. Wright:** I understand that there is a concern on the West Coast, the Boehing Air Transport Company, which is using the metallic welding process in the manufacture of airplane fuselage.

Ordinarily a thin-gage metal is difficult to weld if it is not properly backed up but a skillful operator, with low welding currents, might be able to do it. Whether or not the Boehing Company does it I can't say.

On that gage the current might be from 25 amperes to 75 amperes.

**J. C. Lincoln:** I might give a little experience that was recited to me by Mr. Imlay of the Niagara Falls Power Company. He said that in their plant they had a situation where the pipe was pitting and a hole developed inside the pipe. They drilled the hole out and inserted a lead plug. Subsequently the steel has been eroded all around the lead plug though the plug has not been worn away.

This seems to demonstrate quite completely that this is chemical and not mechanical action. You would expect a lead plug to be eroded much more rapidly than steel pipe under mechanical action.

# Utilization of Lodgepole Pine Timber for Poles

BY R. W. LINDSAY[1]
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***Synopsis.**—With an ever increasing demand for poles used in the construction of power and communication lines, new sources of supply must be developed from time to time. Along the Rocky Mountain Range are found large stands of various species of timber suitable for the production of poles and so far not utilized to any appreciable extent. This paper outlines briefly the selection of lodgepole pine timber for this purpose, relates the past experience with such poles used in certain test lines, and describes in general the production and preservative treatment of the poles.*

* * * * *

## INTRODUCTION

DURING recent years the demand for poles to be used in constructing telephone, telegraph, signal, light, and power lines has increased rapidly. In the eastern part of the United States the cedar stands of Maine have been largely depleted of timber of sufficient size to produce long and large sized poles, and the northern white cedar stands of the Great Lakes region are facing the same situation. Although the blight of the chestnut timber in the Appalachian region has somewhat stimulated the current production of chestnut poles, a large curtailment of the future supply of these poles is inevitable. In all pole producing areas, including the enormous stands of red cedar timber throughout the western coast regions and in the southern pine stands of the South, the hauls are becoming longer, and the charges for stumpage are likely to increase from time to time.

In the face of these conditions, and looking into the future, it has been felt that sooner or later it would be necessary to develop a satisfactory substitute for wooden poles or that new sources of supply must be found. To date, substitutes for wooden poles have not been found to be altogether satisfactory or economical, and it is therefore logical for companies serving the public in sparsely settled territory, necessitating heavy expenditures for pole plant, to look for new sources of pole supply, not only for present consumption but to protect their growing demands of the future.

It has been known for a long time that the Rocky Mountain Range, from New Mexico in the South to Montana in the North, is covered with timber of the proper size to make poles, the principal species available being lodgepole pine, Engelmann spruce, western yellow pine, and Douglas fir. There are various reasons why this timber has not thus far produced many poles, but the chief reason is probably the fact that when these species, with the exception of Douglas fir, are placed in the ground they do not resist the attack of fungi to any great extent. Therefore, it has been recognized that unless a satisfactory treatment could be developed to protect the wood from the infection of fungi, the vast amount of pole timber close at hand could not be economically utilized.

In 1923 an investigation was undertaken by the Mountain States Telephone and Telegraph Company to determine (1) whether or not satisfactory poles could be obtained from the native timber, and (2) whether or not a reliable preservative method could be developed to protect the poles after being placed in the ground. In order to decide whether or not satisfactory poles could be obtained from the native timber, three major questions had to be definitely determined:

a. Whether or not suitable pole-making timber could be found in large quantities in accessible places and close to the railroad.

b. Whether or not, from the standpoints of strength, shape, grain, etc., the timber would be satisfactory.

c. Whether or not poles from this timber could be produced at prices equal to or lower than current prices of other poles.

## AVAILABLE POLE TIMBER

Recent surveys made by the United States Forest Service show the following approximate number of poles that could be produced per acre on certain test sections in several of the national forests of Colorado and Wyoming:

| | |
|---|---|
| Arapahoe Forest | 137 per acre |
| Gunnison Forest | 62 per acre |
| Cochetopa Forest | 47 per acre |
| Leadville Forest | 68 per acre |
| White River Forest | 53 per acre |
| Medicine Bow Forest | 176 per acre |

From sections that have been cut for the purpose of securing ties, sawlogs, props, and poles, and in other sections where special surveys have been made, it has been possible to gain a general idea of the proportion of available poles to the total number of sawlogs and ties that this timber affords. The amount of sawlog and tie timber available in the Colorado and Wyoming National Forests (Wyoming and Teton National Forests in Wyoming not included) is as follows:

| Species | No. of Feet-Board Measure |
|---|---|
| Lodgepole pine | 10,599,078,000 |
| Engelmann spruce | 15,236,420,000 |
| Western yellow pine | 2,031,688,000 |
| Douglas fir | 1,959,289,000 |

From the above information, and allowing fully for

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1. General Engineering Department, The Mountain States Telephone and Telegraph Co., Denver, Colo.

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trees that would not make satisfactory poles, it can be conservatively estimated that there are now in the Colorado and Wyoming National Forests 200,000,000 trees that would make specification poles. These poles range from 20 ft. to 85 ft. in length with the majority under 50 ft. in length. Besides this growth there is an enormous amount of privately owned pole-sized timber here and there along the range. The States of Montana and Idaho also have very large stands of available pole timber on United States national forests. In Colorado, Wyoming, Montana, and Idaho, this timber, consisting mostly of lodgepole pine and Engelmann spruce, can be secured in large quantities within two to ten miles of existing railroad shipping points which are connected with transcontinental railroads, thus making possible comparatively short hauls.

FIG. 1—LODGEPOLE PINE STAND, LEADVILLE NATIONAL FOREST, COLORADO

The timber controlled by the United States Forest Service will always be productive of poles in very large quantities. The cutting is so programmed that the mature timber is cut first, the less mature next, and so on until the crop is either materially thinned or entirely cut. The age of the present mature stands varies from 75 to 300 years. Lodgepole pine reseeds itself, and after being cut a new growth appears in a short time. Reproduction or second growth in pole sizes can be obtained within 75 to 100 years, depending upon the soil characteristics, growing conditions, etc.

These forests contain a large amount of Douglas fir or red spruce timber, and, because of its fungi resistant properties, this variety of timber has been used in the past for railroad ties, mine props, and poles, and found to be very satisfactory. At the present time, however, the stands are located in more or less inaccessible sections and the growth is often scattered. In view of these facts, Douglas fir poles would now cost more than poles cut from either lodgepole pine or Engelmann spruce.

### TIMBER CHARACTERISTICS AND TESTS

In selecting pole material, the fiber strength in bending is a very important consideration. The strength of pole timber is usually determined by testing the poles in a device by means of which the load, distances from the load to the supports, and the deflections can be accurately measured; and practically all tests of lodgepole pine timber have been made in a standard laboratory testing machine.

Comparative tests[2] of lodgepole pine, Engelmann spruce, and cedar poles were made in 1911 at the University of Colorado, Boulder, Colorado, by Norman Betts and A. L. Heim, engineers in forest products. Twenty western red cedar poles, which were cut near Edgemore, Idaho, and purchased on the Denver market; 22 lodgepole pine poles, cut in the Deerlodge National Forest, Montana; besides 20 lodgepole pine poles and 20 Engelmann spruce poles, fire-killed ten years and cut in Colorado, were all shipped to the University of Colorado for these tests. The strength in bending was determined by placing the poles in a Riehle testing machine and applying a load until failure occurred, and the fiber stress at elastic limit, modulus of rupture, stiffness factor, and modulus of elastic resilience were determined for all poles considered. In addition, the moisture content, annual rings per inch, proportion of heartwood and sapwood, and the weight per cubic foot were determined. The general results of these tests were as follows:

1. Air-seasoned lodgepole pine is superior to western red cedar in all the mechanical properties determined.
2. Fire-killed lodgepole pine is only 80 per cent as strong as western red cedar at maximum load.
3. Fire-killed Engelmann spruce poles are inferior to cedar and pine in all mechanical properties.

The comparative average strength of the cedar, air-seasoned and fire-killed lodgepole pine, and the fire-killed Engelmann spruce is shown clearly in the following table:

| | Moisture Content | Pounds/Sq. In. Modulus of Rupture | Pounds/Sq. In. Fiber Stress at Elastic Limit |
|---|---|---|---|
| Western red cedar | 15.1 | 6,885 | 4,430 |
| Lodgepole pine (air-seasoned) | 21.9 | 7,680 | 5,280 |
| Lodgepole pine (fire-killed) | 16.9 | 5,481 | 4,327 |
| Engelmann spruce (fire-killed) | 16.3 | 4,378 | 3,489 |

In 1926 the Mountain States Telephone and Telegraph Company made similar tests of 53 lodgepole pine poles. All the poles were cut green in the Sargents, Pitkin, and La Veta Pass districts of Colorado. Thirty-one of the poles tested were open tank-treated with creosote, the temperature of the hot bath during the creosote treatment having ranged between 200 deg. and 260 deg. fahr. These poles were shipped to the University of Colorado, at Boulder, and there tested in the same Riehle machine that was used by Betts and Heim in 1911. To determine the modulus of rupture, the poles were placed in the machine in 20-ft. lengths in order to allow both ends of the pole to rest on the bed of the machine. The load was applied at a uniform speed of approximately one in. per min. The deflection of the pole was noted at intervals of 1000 lb. until a total load of 6000 lb. was reached, after which the machine was kept in balance, the deflection being noted at 250 lb. intervals until failure occurred. The characteristics of each fracture were carefully examined, and data were tabulated regarding the relative location of large knots, the type of fracture and whether or not the pole failed in tension or compression. In the tests the annual rings per inch, twist in grain per 20 ft., taper, moisture content, and specific gravity were also determined.

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[2] This report is covered in detail by *Bulletin No. 67*, U. S. Dept. of Agriculture, dated March 17, 1914.

FIG. 2—RIEHLE TESTING MACHINE AT UNIVERSITY OF COLORADO

The main conclusions drawn from these tests were as follows:

1. The open tank treatment of the poles did not show a positive tendency either for increasing or decreasing the strength of the pole.
2. A slight tendency toward an increase of strength with a decrease in moisture content was noted.
3. Large knots or rings of knots were found very objectionable from the standpoint of strength.
4. The modulus of rupture for the 53 pieces averaged 7723 lb. per sq. in. The average moisture content was 15.98 per cent.

Among those who witnessed these tests were Messrs. H. N. Biggle and S. E. Horton of the Western Union Telegraph Company, Professors H. J. Gilkey and Clarence L. Eckel of the University of Colorado, and Professor W. C. Huntington of the University of Illinois. In this work the University of Colorado heartily cooperated with and assisted the telephone company representatives, as well as providing the mechanical laboratory and the necessary space in the chemical laboratory for the tests.

In 1927 the Bell Telephone Laboratories made tests of pressure-treated creosoted lodgepole pine poles at the University of Colorado. The average modulus of rupture determined in these tests was 6214 lb. per sq. in.

When considered as to shape, grain, and other physical characteristics necessary for satisfactory pole material, all species,—that is, Engelmann spruce, lodgepole pine, Douglas fir, and western yellow pine, would qualify and would rank in the order named in so far as desirability is concerned. This rating is determined by an examination of the timber after it is cut into poles, noting the taper, the size of knots, the twist in grain, the thickness of sapwood, the extent of undesirable scars, and other features inherent in its growth. Western yellow pine grows generally in rather open areas, is found in large trees and has large knots; moreover, extensive pole producing areas are scarce.

### PRODUCTION COSTS

At the time this investigation was made, all cost figures as to stumpage, cutting, skidding, hauling, and loading poles on the cars indicated that poles in most of the available Rocky Mountain areas could be produced at equal or less cost than those shipped in from other sources of pole supply, with the possible exception of southern yellow pine in some districts.

In connection with the cost of producing poles in this territory, the freight factor is very important. For example, poles can be delivered in Colorado from the pole producing areas of either Colorado or Wyoming at a freight rate less than one-half the rate from other sources.

### LODGEPOLE PINE AND EXPERIMENTAL LINES

The lodgepole pine, because of its existence in such large quantities and in such favorable locations from a cutting and shipping standpoint, and also due to its greater fiber strength than that of the Engelmann spruce, was chosen as a logical pole timber with which to experiment.

It was recognized that the successful and profitable utilization of lodgepole pine timber for poles could not be expected unless a satisfactory treatment could be employed that would be effective in protecting the wood from rotting after the poles were placed in the ground; and it is now an established fact that this timber can be so protected, as shown by experience with the following lines.

In 1909 at Norrie, Colorado, 1022 fire-killed lodgepole pine poles were butt-treated with creosote oil. The treatment consisted in placing them in a vat containing the oil, which was heated for a sufficient time, allowed to cool and then drawn off. In this process a penetration of from one-eighth inch to one-fourth inch was obtained, which under present day methods is considered shallow penetration. One very important factor which favored these poles was that they were fire-killed and thus perfectly seasoned, and therefore checked very little after they were placed in the lines. Of these poles 561 were placed in service in Rifle, Colorado, by the Rifle Heat and Power Company, and a line was also built extending from Rifle to their power plant, a distance of approximately 12 mi. These poles were inspected in 1917, 1920, and again in 1926. After 17 years' service, 88.4 per cent of the poles were found to be sound, 2.6 per cent contained decay, and 9 per cent had been removed. All tops were inspected and only one pole showed signs of decay above the ground.

In 1910 the Mountain States Telephone and Telegraph Company placed in service 759 poles which were fire-killed and treated at Norrie in the same manner as the poles placed at Rifle. They were used in a line between Hotchkill and Crawford, Colorado, and to this date, after 18 years' service, no replacements have been made, although 42 poles have been reset and 10 have been reinforced.

Studies of pole line inspection reports show that very few poles in the Rocky Mountain territory become infected and rot above the ground line. This is probably due to the lack of moisture necessary to fungi growth. For this reason it is felt that in this territory it is neither necessary nor economical to treat poles above the ground line.

In the light of this past experience, it is reasonably certain that, when seasoned and properly butt-treated with dead oil of coal tar, lodgepole pine poles will prove both satisfactory and economical for the construction of power and communication lines throughout large areas of the West.

## PRODUCTION

Tentative specifications for lodgepole pine poles were drafted in 1924. In general, these specifications followed those for southern yellow pine poles, taking into consideration, however, the characteristics of the lodgepole pine timber. In November, 1926, specifications for lodgepole pine poles and the creosote treatment thereof were drafted by engineers of the American Telephone and Telegraph Company. These specifications were based upon the experience gained in handling, inspecting, and treating these poles and the tests made to determine their strength in bending. These specifications are still in force.

In 1924 arrangements were made with a timber company to cut approximately 10,000 lodgepole pine poles in the vicinity of Sargents and Pitkin, Colorado. Due to the fact that any oil treatment is of little value in this territory unless the poles are properly seasoned, an effort was made to cut these poles so that they would season during the months of June, July, and August previous to their shipment to the treating plant the following January and February. In the seasoning process the moisture content reduces from 60 to 90 per cent to 20 to 25 per cent. The moisture content is determined by removing a core from the pole, drying it in an oven, and calculating the ratio of the loss of moisture to the dry wood. The seasoning is valuable for three reasons:

1. It reduces the weight of the pole, thereby effecting savings in freight and hauling charges.
2. The shrinkage in the wood fiber produces checks which can be stapled and controlled before the pole is treated and placed in service.
3. Poles having a heavy twist tend to straighten out when seasoning. If poles are placed in the line when green, the gains become out of line as the poles season, which, in some cases, necessitates regaining and retying the wires in order to relieve the tension on one side of the arm.

In an endeavor to control the checking of the poles after they have been treated, anti-splitting staples are used for controlling large season checks. These staples are driven into the poles, spanning the checks to prevent further opening. This practise is also employed to control checks in western cedar poles. During the seasoning process small poles shrink from ¾ in. to 1 in. in circumference, while large poles shrink from 1½ in. to 2½ in. in circumference, depending upon the size of the pole, the age of the tree, and other factors. It is therefore absolutely necessary that poles be cut from six to nine months in advance of using them, in order that they may be properly seasoned. It is also more economical for the producer to cut poles when the sap is up and the bark can be removed easily, which period is generally between the fifteenth of April and the first of August. All cutting operations, of course, cannot be done during this time, but it is a great aid to the cutter if he can cut and peel a large number of his poles at this opportune time.

In most cutting areas it is more economical to haul the poles from the woods to the railroad on snow with sleds than any other way, although in a few localities, where road conditions permit, probably a wagon or tractor could be operated satisfactorily, but in general such a method is expensive. After being cut, limbed, and peeled, the poles must be skidded to the roads, sorted fairly well according to size and class, and placed on timbers to minimize the chance of becoming infected with fungi growth and to aid in their further seasoning. The weather conditions vary along the range from year to year, and it is generally difficult to haul poles before the first of December following the cutting operation. After snow falls in large enough quantities to permit sledding, the poles are hauled to the railroad and there placed on skids, assorted by classes and lengths to await inspection.

It can readily be seen that it is necessary to program carefully the pole requirements far enough in advance to allow the producer to cut and haul the poles at the most economical time and still have the proper time for seasoning.

Returning to the activities of the Mountain States Telephone and Telegraph Company directed toward determining the feasibility of lodgepole pine pole production, and referring to the arrangements made in 1924 for the cutting at Sargents, Colorado, after these poles were fairly well seasoned in the woods or at landing yards along the railroad, they were shipped to Salida, Colorado, for treatment.

### PRESERVATIVE TREATMENT

In the meantime an open tank creosoting plant was constructed at Salida, Colorado, for the purpose of treating poles. Salida was selected as the logical location for this plant, due to the fact that it is near the center of the pole producing timber on the Denver and Rio Grande Western Railroad, and a junction point of the narrow and standard gage routes of this system. The vats of this plant were constructed in general according to plans furnished by the American Telephone and Telegraph Company. There are two treating vats 9 ft. wide, 24 ft. long, and 10 ft. deep. In the bottom of each vat is a steam coil protected by a steel grid. There are two storage tanks for the dead oil of coal tar, one called the cold tank and the other called the hot tank, each containing a heating unit to maintain the oil at the proper temperature. The heating unit in the cold tank maintains the temperature of the oil at approximately 100 deg. fahr. in winter weather and by circulating cold water through this unit during the summer time, the cold oil can be kept at a temperature of approximately 100 deg. fahr. The vats and tanks are supplied with steam from a 40-hp. boiler and under a pressure of 45 lb. per sq. in. A pit is located between the treating vats, in which is mounted a centrifugal pump driven by an electric motor; and the vats, pump, and tanks are connected with eight-inch pipe lines. This arrangement provides for pumping the oil rapidly out of the vat after the hot treatment and pumping cold oil back into the vat to continue with the cold treatment.

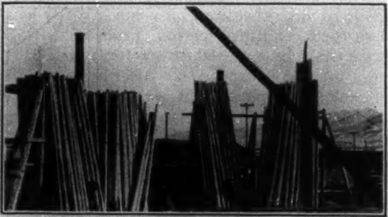

FIG. 3—LODGEPOLE PINE POLES IN TREATING VATS, SALIDA, COLORADO

Experiments supervised by the Department of Development and Research of the American Telephone and Telegraph Company were carried out to determine the proper preparation of the poles and the character of the treatment which would produce the best results. In order to insure even and deep penetration, it was found necessary to remove all pink bark on winter cut poles and also the transparent skin on summer peeled poles. The necessary shaving of the poles was done with an ordinary draw knife. It was also found that the most desirable results could be obtained by treating the poles in a hot oil bath for seven hours at a temperature of from 225 to 250 deg. fahr., after which the hot oil was replaced quickly with cold oil and the treatment continued for an additional seven hours at a temperature of from 100 to 110 deg. fahr. With this treatment a penetration of oil was secured ranging from ⅝ in. to 2½ in. with an absorption averaging 2.2 gal. per pole. It was found that by raising the temperature of the hot bath from 225 to 250 deg. fahr. the absorption of oil greatly increased. Tests were made to determine whether or not this heat affected the strength of the pole, and it was found that it did not materially do so.

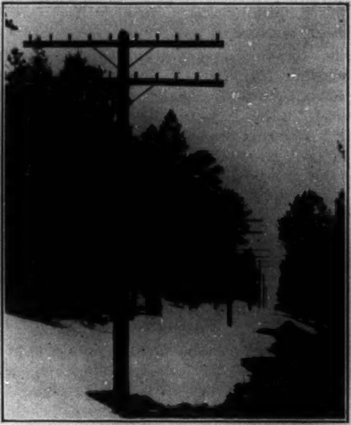

FIG. 4—LODGEPOLE PINE POLE LEAD NEAR DENVER, COLORADO

Test pieces of Douglas fir were treated, and it was found that very little penetration could be secured. Lodgepole pine generally has a thick sapwood while that of Douglas fir is relatively thin. In either species under ideal conditions the sapwood can be penetrated, but very little, if any, penetration can be secured into the heartwood. Tests of fire-killed lodgepole pine timber were made, and it was found that a penetration of more than one-half inch was impossible, regardless of the temperature of the hot bath. In this connection it was impossible to locate stands of suitable fire-killed lodgepole pine in Colorado.

During 1925 approximately 3500 poles were shipped to Salida, where they were prepared for treatment, treated, and reshipped to their destination. The following year 21,000 poles were cut in the vicinity of Sargents, Pitkin, and La Veta Pass, Colorado, treated at Salida and placed in lines in Colorado, Wyoming, and

Utah. In 1927, 16,000 poles were produced in the same locality. In 1927 arrangements were made to expand the production, and contracts were made with a producer on the Moffat Railroad near Phippsburg, Colorado, and one on a branch railroad near Laramie, Wyoming, with the result that the total production in 1928 will be in the neighborhood of 35,000 poles. As the production and consumption of these poles increases, producers should be secured in Montana and Idaho.

## CONCLUSION

There is every reason to believe that tank treated lodgepole pine poles will have an average life in service of at least 15 to 20 years, and possibly longer. There are many factors that affect the ultimate wire load of a telephone pole line, and often this load increases faster than was originally anticipated, with the result that the pole is found to be undersized long before it has been condemned; also, at times other unforeseen factors necessitate moving the pole before its life has been spent. In this territory it now appears that a pole with the lowest possible first cost and a fairly long life is more economical than a pole with a higher first cost and longer life. In other parts of the United States where the density of poles is greater and poles can readily be recovered and reset without damaging the treated portion, different conclusions may be reached.

From the foregoing outline of the investigations thus far made to determine the field of usefulness offered by lodgepole pine timber as a source of pole supply, there can be found justification for continuing and expanding this production, with full confidence that through the employment of proper methods of cutting, seasoning, and treating, lodgepole pine poles will prove highly satisfactory for the construction of the ever increasing number of power and communication lines traversing the western plains and Rocky Mountain region.

# Carrier Systems on Long Distance Telephone Lines

BY H. A. AFFEL[*], Member, A. I. E. E., C. S. DEMAREST[*], Member, A. I. E. E., and C. W. GREEN[†], Member, A. I. E. E.

***Synopsis.**—A previous Institute paper in 1921 gave a very complete résumé of the activities of the Bell System at that time in the development of multiplex telephone and telegraph systems using carrier-current methods. A new type of carrier telegraph system was subsequently described in an Institute paper. In the present paper the authors describe developments which have resulted in improvements in the carrier telephone art since that time. A new, so-called type "C" system is described in detail, together with suitable repeaters and pilot channel apparatus for insuring the stability of operation: the line problems are considered and typical installations pictured. The growth of the application of carrier telephone systems and their increasingly important part in providing long distance telephone service on open-wire lines are shown.*

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## INTRODUCTION

At the Midwinter Convention of the Institute in 1921, Messrs. Colpitts and Blackwell presented a paper entitled *Carrier Current Telephony and Telegraphy*, TRANS. A. I. E. E., Vol. XL, 1921, p. 205. This described the development work of the Bell System which had resulted in the production of commercial types of multiplex telephone and telegraph systems using carrier-current methods. The paper also gave a brief historical summary and included a theoretical discussion of the methods involved, as well as detailed descriptions of apparatus which had found employment in the telephone plant.

The carrier-current art had at that time emerged from the laboratory to play its part in meeting the practical requirements of telephone service in the field. This step was made possible largely by two tools, now indispensable to the communication engineer, the thermionic tube and the wave filter.

In an ordinary telephone circuit, each frequency component in the voice of the speaker is transmitted by an electrical current of the same frequency. In most cases the electrical equipment of the circuit is not called upon to transmit frequencies above about 3000 cycles per sec. In carrier-current operation, however, the voice-frequency currents are caused to modulate a high-frequency current which thus serves as a "carrier" for the message. In this way an additional telephone channel is obtained, using frequencies entirely above those transmitted in connection with the ordinary voice-frequency channel. By using other high frequencies, several additional messages may be transmitted simultaneously on the same pair of wires. Each channel occupies a certain range of high frequencies. For example, the words of one speaker may be conveyed by a channel employing frequencies from about 23,500 to about 26,000 cycles per sec. At the receiving terminal the various incoming ranges of high-frequency currents are separated by electrical filters. Then by demodulation the original voice-frequency currents are produced again and are transmitted over voice-frequency circuits, the transmission over each channel thus reaching the proper listener. In this way a telephone line already carrying d-c. telegraph and voice-frequency telephone services may be multiplexed so as to provide additional telephone facilities. In a somewhat similar manner the high-frequency range may be used instead to transmit telegraph messages. In the present paper, carrier telephony alone is considered.

The Colpitts-Blackwell paper described two carrier telephone systems which had been developed up to that time, a four-channel "carrier suppressed" system (type *A*), and a three-channel "carrier transmitted" system (type *B*). The initial installation of these systems was made about 1918 on the long lines of the Bell System.

These earlier systems were effective in bringing about economies by avoiding the stringing of additional wire on many long pole lines, but there remained many opportunities for further improvement in performance and simplification of equipment. New problems arose to be solved in connection with the desire to operate the largest possible number of systems on the same pole line. The result has been the development of a substantially improved technique and a new system (the type *C*) which not only has provided much improved performance over its predecessors but which has led to further economies because of reduced costs.

*Carrier Telephone Growth in Bell System.* Whereas the use of the early types of systems was justified in competition with the alternative of additional wire stringing only for distances exceeding 250 to 300 mi., the new system proves economical for distances considerably less. This fact has naturally stimulated the application of carrier telephony in the Bell System. This is shown by Fig. 1, which indicates the growth of these systems in terms of channel mileage afforded by their use. It will be noted that the rate of growth of the systems has increased greatly in the last two or three years, a result of the availability of the improved system.

At the end of 1927 there were in operation about

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[*] Dept. Development and Research, American Telephone and Telegraph Company.

[†] Bell Telephone Laboratories, Inc.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

130,000 channel miles. By the end of 1928 the figure is expected to be about 230,000. This figure does not, of course, represent a very large proportion of the total toll mileage of the Bell System, which includes many circuits less than 100 mi. in length. It is sufficient, however, to indicate that the carrier telephone systems are a substantial factor in the provision for the growth of the longer haul facilities, where they naturally provide the greatest economies. Their use is, of course, restricted to sections of the country in which open-wire construction is chiefly employed.[1] They have contributed toward lowering the cost of service and in making possible the toll rate reductions which have been put into effect within the past year or so.

*New System Replacing Older Types.* The new type *C* system is essentially a long-haul, multi-channel system. It adds three high grade telephone circuits to the facilities normally afforded by a single pair of wires, and can be used over any distances likely to be encountered in the Bell System. Where repeaters are required they are spaced at intervals of 150 to 300 mi., depending upon particular transmission considerations. Stability of transmission over the several carrier channels is assured, despite the relatively large inherent variations in high-frequency line transmission due to weather changes, by means of a pilot channel.

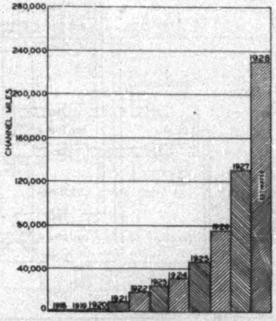

Fig. 1—Growth of Carrier Telephony in Bell System

The service requirements which present themselves in the application of carrier methods are, of course, basically no different from those for commercial talking circuits obtained by other means. The problem is to establish a toll circuit between long distance offices which meets certain standards of transmission, including speech volume, stability, and quality. The latter requires that there must be transmitted a certain band width of frequencies in the voice range. Furthermore, there must exist no appreciable load distortion effects. The circuit must also be relatively free from noise or cross-talk. A signaling system must be provided so that the operators at opposite terminals may call each other. In other respects the system must appear as a normal telephone circuit not distinguishable from an operating standpoint from the other circuits afforded by metallic wire connections. The apparatus installed in the telephone office must conform to certain physical standards of equipment, sturdiness, flexibility, etc. It must be capable of being maintained by trained office forces. Testing facilities must be provided, etc. It is believed that these objectives have been largely realized in the arrangements which are described in this paper.

## THE TYPE *C* SYSTEM

The type *C* system embodies those major technical features which our experience with the older systems has indicated as most desirable. It is a carrier-suppressed, single sideband system, in which respect it is similar to the older type *A* system. However, it has been found possible to dispense with the equal frequency spacing of the channels which was characteristic of the type *A* system, and which involved the transmission of a synchronizing current between two terminals and the harmonic generation of higher frequencies from this synchronizing current. A simplification in apparatus has resulted. This non-harmonic arrangement of channels has further made possible a more efficient use of the frequency spectrum by the fact that the channel bands at lower frequencies can be squeezed together more closely than those of the higher frequencies where the band filters are less efficient due to decreasing ratio of band width to frequency.

The type *C* system requires for each modulator an oscillator as a source of carrier supply. Moreover, since a synchronizing current is not employed at the receiving terminal of the channel an oscillator of the same frequency is required for "demodulation." Advances in the art of designing vacuum tube oscillators of great frequency stability have made it possible to insure that these oscillators, which may be hundreds of miles apart, remain sufficiently close together in frequency so that no noticeable impairment in quality of transmission results.

In the matter of the frequency allocation of the channel bands, the type *C* system possesses one of the essential features of the older type *B* system, that is, the use of different carrier frequencies for transmission in opposite directions. Comparative experience with the type *A* system which, by means of high-frequency line and network balance, employed the same frequency band for the opposite directional paths of the channel led to the conclusion that the systems which avoided the high-frequency balance requirement were more desirable. Also the problem of intermediate repeater amplification is simplified where the opposite directional frequencies are thus separated and grouped. Furthermore, the cross-talk problem between different systems on the same pole line is greatly simplified for reasons which will be discussed later, and a greater total number of channels may usually be obtained on the same pole line.

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[1] In localities having very heavy traffic requirements such as in the East, extensive use is made of toll cables.

The single sideband transmission employed reduces by about one half the frequency band that would otherwise be required for each channel. The carrier is not transmitted, as the presence in the system of carrier currents of the large magnitude required for a "carrier transmitted" system not only requires greater amplifier load capacity at the repeaters, but may increase the possibility of troublesome cross talk and noise interference. The selectivity requirements of the band filters would also become more severe to keep the carrier of one channel out of the other channels in the system.

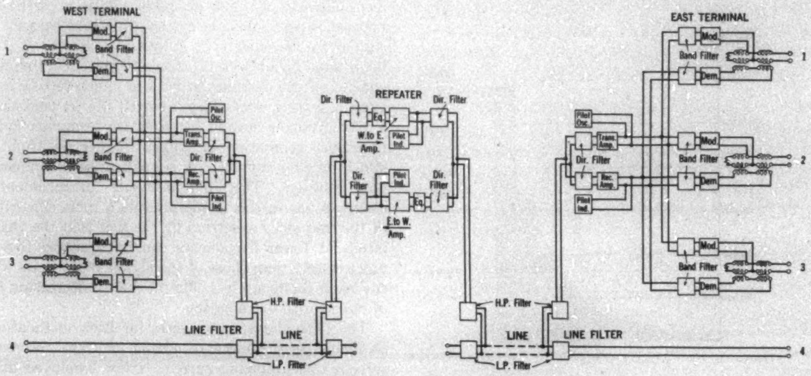

FIG. 2—A COMPLETE CARRIER SYSTEM SCHEMATIC

*A Complete System.* The simplified layout of a complete system is shown in Fig. 2. It will be noted that it includes apparatus at a terminal, a line circuit, a repeater station, a second line circuit, and apparatus at a second terminal. Obviously, the total line length between terminals may be extended by the use of a greater number of repeaters.

At each end there are the terminations of the three carrier channels 1, 2, and 3, and the regular voice circuit 4. These terminations appear, of course, at the long distance switchboard in the same office or in a different office from the carrier terminal. When a subscriber is connected to one of the terminations, for example, No. 1, speech currents pass through the three-winding hybrid coil, thence into the modulator circuit where they are caused to modulate high-frequency carrier current. The resultant modulated bands[2] of frequencies pass through a band filter allowing only the desired band to pass to the transmitting amplifier, thence this band passes through a so-called directional filter and a high-pass filter to the line circuit. The high-pass filter last referred to, in association with its complementary low-pass filter, forms a so-called "line filter" set whereby the regular voice range currents are separated from the higher frequency carrier current at both terminal and repeater offices.

The other two carrier channels function similarly, and the several modulation bands of carrier frequencies join the first channel in passing through the common amplifier and directional filter circuit to the line. At the repeater point the group of bands comprising the three channels passes through the high-pass line filter circuit, thence through a directional filter and line equalizer to the amplifier circuit and outward through the directional and line filter circuit to the next line section. At the farther terminal the combined carrier currents pass through the directional filter and are again amplified in the receiving amplifier. At the output of the amplifier the different carrier channel bands of frequencies are selected one from another by the band filters, thence they pass to the demodulator circuit, are demodulated to their original form and then pass from the output connection of the hybrid coil to their respective terminations.

*Circuit Arrangements at Terminals.* Fig. 3 shows diagrammatically in somewhat greater detail the terminal of the type *C* system. The modulator circuit consists of a two-tube "push-pull" grid-bias vacuum tube circuit in which the carrier frequency is balanced out. A separate oscillator tube circuit of exceptional frequency stability supplies the carrier. The frequency allocation requires the transmission of only the upper or lower sideband frequencies, and the band filter at the output selects the desired band, rejecting the other products of modulation as well as the amplified voice frequencies which are incidentally transmitted through the modulator unit. This sideband current in conjunction with the corresponding currents of the other two sidebands of the outgoing channels passes through the common amplifier. This is a two-stage vacuum tube unit having four tubes in the output circuit arranged in parallel push-pull connection to insure the required load carrying capacity.

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[2] For a discussion of modulation see E. H. Colpitts and O. B. Blackwell, *Carrier Current Telephony and Telegraphy*, A. I. E. E. TRANS., Vol. XL, 1921, p. 205; R. V. L. Hartley, "Relation of Carrier and Side Bands in Radio Transmission," *Bell System Tech. Jl.*, Vol. 2, April 1923, pp. 90-112.

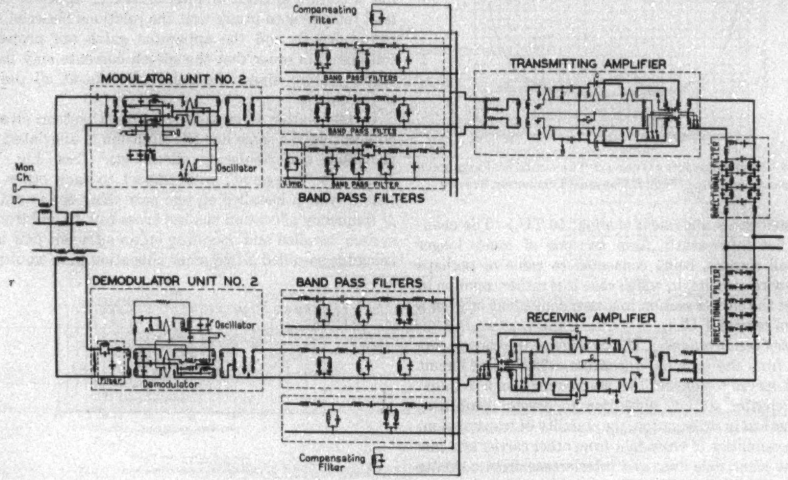

FIG. 3—SCHEMATIC DIAGRAM OF TYPE *C* TERMINAL CIRCUIT

The circuit then leads through a directional filter of either low-pass or high-pass type which distinguishes between the band groups of the opposite directions of transmission as required by the allocation of frequencies. The amplified currents pass through the high-pass filter of the line filter set and thence to the line circuit.

In receiving, the sideband frequencies after separation from the voice currents by the line filter set, pass through the directional filter and an amplifier similar to that used at the transmitting terminal. While the power output required at the receiving amplifier is usually small as compared to that required at the transmitting amplifier, the same unit is used for the two positions to provide flexibility in the adjustments of the receiving gains of the separate channels and for the purpose of economy in production. The different channel currents in the output of the amplifier are selected by the respective receiving band filters and thence pass into the demodulator circuits. In the demodulators the voice frequencies are derived by the modulation of the sideband currents with a carrier frequency supplied by a local oscillator whose frequency is adjusted accurately to agree with that of the corresponding transmitting modulator at the farther terminal. This important problem of synchronization of oscillators is further discussed later in the paper. It is, of course, obvious that if the carrier frequencies of the modulator and the corresponding demodulator of the same channel are not in sufficiently close agreement there will be a serious distortion of the speech currents received over the channel.

The output of the demodulator circuit includes a low-pass filter for suppressing the unwanted components of demodulation, and the circuit thence leads to the channel terminal through the hybrid coil. The function of the latter is to provide a two-wire termination of the channel and it prevents the output currents of the demodulator from reaching in any substantial magnitude the input of the modulator circuit, thus setting up a regenerative action which might result in "singing."

It may be noted that the circuit normally provides for a transmission "gain" or amplification of energy from the switchboard termination to the high-frequency line circuit of approximately 20 TU[3] corresponding to a current or voltage amplification of 10 to 1. In the receiving direction a gain of the same order of magnitude is also available. Of course, the exact amount utilized in a particular case depends on the line attenuation and the desired over-all equivalent of the circuit. It is usually desirable at the transmitting terminal to maintain the level at the maximum possible for the system. The over-all transmission afforded by a carrier system may be noted by the curve on Fig. 4, which shows the relative speech frequency transmission characteristics of a typical channel. Where the carrier channel is employed for terminal-to-terminal business the over-all equivalent at 1000 cycles is ordinarily adjusted to an equivalent of about 10 TU. The channels not infrequently form sections of much longer over-all circuits, being connected to cable or perhaps open-wire circuits, in which case it is rather common to adjust the carrier section to a zero equivalent or even a gain of several T U.

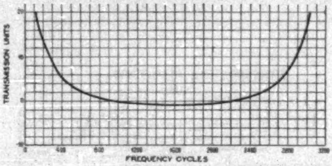

Fig. 4—Representative Over-all Transmission-Frequency Characteristic—Type *C* Carrier Telephone System

*Line Considerations.* The passage of the carrier currents from the terminal apparatus over the line circuit which serves to connect the two terminals, or a terminal and repeater station, gives rise to several problems: the line loss or attenuation, the stability of transmission, the possibilities of cross-talk from other carrier systems on the same pole line, and interference from currents from external sources. These factors must be considered not only in connection with the arrangement of the wires themselves but also in conjunction with the design of the terminal apparatus, repeaters, etc., so that satisfactory over-all speech transmission may result.

As was brought out in the Colpitts-Blackwell paper, the line attenuation at the high frequencies is in accord with the recognized transmission theory. Because of skin effect in the wires and rising losses in the insulators the attenuation increases steadily with frequency. Unfortunately the losses at the insulators are not constant and they increase greatly with the presence of moisture. This brings about an increase in attenuation in rainy weather. Fog, sleet, and wet snow may greatly increase these attenuation changes. There is also a lesser source of variation due to temperature change and its effect on wire resistance.

If care is not taken the carrier currents may be interfered with on the line circuits by cross-talk from other carrier systems and by miscellaneous currents which enter the circuit by induction from the outside. These latter manifest themselves as noise in the carrier channels. This makes it essential to use only the metallic circuit, *i. e.*, two wires well balanced to ground for transmitting the carrier currents. The balance to ground must be maintained at a high degree by frequent transpositions in the wires. Even with these precautions unavoidable residual unbalances may permit a certain amount of interference to appear. The final remedy is to insure that the relations between the circuit length and the apparatus gains are properly considered in order that the speech currents may have ample margin above the noise currents at all points in the circuit.

In the matter of cross-talk between systems closely adjacent on the same line the situation is alleviated by providing two frequency allocations. (See Fig. 5.) These are "staggered" with respect to each other, so that a system installed on one pair using the so-called *N* frequency allocation has less cross-talk to and from a system installed and operating on an adjacent pair and using the so-called *S* frequency allocation than would be the case if both systems employed the same allocation. The maximum upper frequency required is raised only slightly by this arrangement.

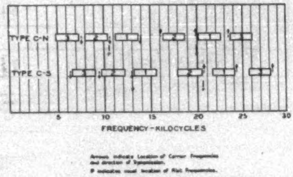
TYPE C-N
TYPE C-S
1
2
5
10
15
20
25
30
FREQUENCY-KILOCYCLES
Arrows indicate Location of Carrier Frequencies and direction of Transmission.
P indicates usual location of Pilot Frequencies.

Fig. 5—Frequency Allocations of Type *C* System

*Repeaters.* Repeaters must be employed when the distance exceeds that for which terminal transmitting apparatus is effective in maintaining the transmission level well above the line noise. The function of the repeater is, therefore, to amplify the carrier currents so that they pass on to the succeeding line section at a magnitude comparable to that sent out from the terminals. Obviously, the design of the repeater with respect to its gain and level carrying capacity, etc., presents a wide range of possibilities, depending on the distance of transmission, frequency, etc.

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[3] R. V. L. Hartley, "The Transmission Unit," *Electrical Communication*, Vol. 3, No. 1, July 1924, p. 34; W. H. Martin, *Transmission Unit and Telephone Transmission Reference System*, Trans. A. I. E. E., Vol. XLVIII, 1924, p. 797, *Bell System Tech. Jl.*, Vol. 3, July 1924, pp. 400-408.

It has been found most practical to install the repeaters along the route at approximately the spacing of the voice-frequency repeaters on the same wires. This means a spacing of from 150 to 300 mi., and occasionally slightly over 300. To have in the same office both voice-frequency and carrier repeaters reduces the equipment, simplifies the maintenance problem, and makes it possible to use the same sources of power supply. The gain and the load carrying capacity are, therefore, determined by this spacing, the gain being controlled by the attenuation loss between the repeaters, and the load carrying capacity by the output level desired because of noise considerations.

The higher attenuation of the line in the carrier range of frequencies means that the carrier repeaters must have a maximum gain of approximately four times that of the voice repeaters operated on the same wires. Whereas gains of the order of 8 to 15 TU may be readily supplied by voice repeaters using balance and so-called "two-wire" operation, the 30 to 45 TU gain required by the carrier repeaters necessitates non-balanced or "four-wire" operation or its equivalent, by using different frequencies in opposite directions and directional filters for the prevention of "singing."

Fig. 6 is a schematic diagram of the circuits comprising a typical repeater station including loading, compositing apparatus, and line filters. After passing through the high-pass line filter the carrier currents arrive at the high and low group directional filters which distinguish between the oppositely directed currents. These filters are substantially the same as those used for similar purposes at the terminal stations.

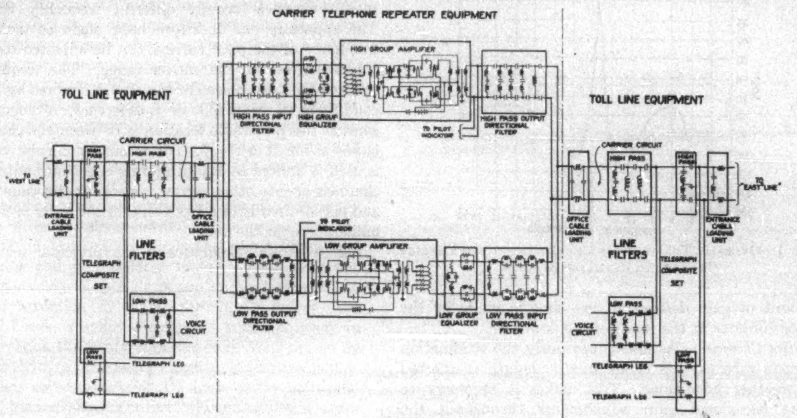
CARRIER TELEPHONE REPEATER EQUIPMENT
TOLL LINE EQUIPMENT
TOLL LINE EQUIPMENT
HIGH GROUP AMPLIFIER
HIGH PASS INPUT DIRECTIONAL FILTER
HIGH GROUP EQUALIZER
TO PILOT INDICATOR
HIGH PASS OUTPUT DIRECTIONAL FILTER
CARRIER CIRCUIT
HIGH PASS
HIGH PASS
TO "WEST LINE"
ENTRANCE CABLE LOADING UNIT
OFFICE CABLE LOADING UNIT
LINE FILTERS
TELEGRAPH COMPOSITE SET
LOW PASS
VOICE CIRCUIT
LOW PASS
TELEGRAPH LEG
TELEGRAPH LEG
TO PILOT INDICATOR
LOW GROUP AMPLIFIER
LOW PASS OUTPUT DIRECTIONAL FILTER
LOW GROUP EQUALIZER
LOW PASS INPUT DIRECTIONAL FILTER
CARRIER CIRCUIT
HIGH PASS
HIGH PASS
TO "EAST LINE"
OFFICE CABLE LOADING UNIT
ENTRANCE CABLE LOADING UNIT
LINE FILTERS
TELEGRAPH COMPOSITE SET
LOW PASS
VOICE CIRCUIT
LOW PASS
TELEGRAPH LEG
TELEGRAPH LEG

FIG. 6—GENERAL SCHEMATIC OF CARRIER REPEATER CIRCUIT WITH ASSOCIATED LINE EQUIPMENT

It is, of course, required in the design of the directional filters that in each direction the filters must pass a frequency band sufficient to transmit properly the three carrier channel bands. In addition to this the filters must present a loss outside of the transmission band which is sufficient to prevent the two-way amplifier circuit from "singing." This means that considering the closed loop circuit of the two amplifiers and the four directional filters the attenuation in this loop must be considerably greater than the sum of the gains or amplification of the two amplifiers. There are also other requirements which these filters must meet which are discussed later.

The amplifiers are the same as used for group amplification purposes at the terminals. Each consists of a two-stage reactance-coupled vacuum tube circuit having four tubes in parallel push-pull connection in the output circuit. The carrying capacity of this amplifier with the standard plate voltages is about one watt in the output, and the over-all amplification or gain including incidental filter losses is about 30 TU. Where gains greater than 30 TU are necessary in the higher frequency group provision is made for the addition of an amplifier stage ahead of the unit shown, which adds approximately 15 TU gain. At the same time provision is made for the addition of greater directional filter selectivity.

An important feature of the repeater circuit is the equalizer which is connected ahead of the amplifier. Because the line circuit attenuation varies with frequency and is greatest at the higher frequencies, it is necessary that the amplification introduced at a repeater point be varied with frequency. The amplification introduced by the amplifier unit itself is substantially uniform with frequency. The equalizer network, however, by introducing a loss which is a minimum at the highest frequency of transmission and which increases for the lower frequencies makes the over-all repeater amplification a function of frequency and in general proportional to the line attenuation which it is designed to overcome.

A typical over-all gain characteristic of the repeater is shown in Fig. 7. The adjustment of the exact amount of gain desired at any time is made by the potentiometer at the input of the amplifier.

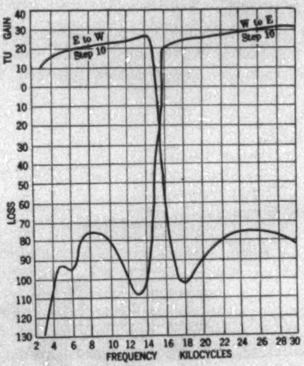

Fig. 7—Over-all Transmission Characteristics of Carrier Telephone Repeater Station

*Pilot Channel.* As noted previously the attenuation of open-wire circuits of substantial length is affected by weather conditions. This makes it necessary to make occasional gain adjustments throughout the system. The extent of these adjustments is determined by means of the pilot channel which provides a visual indication of the transmission levels of the carrier system in both directions of transmission without interfering with the speech currents over the channels themselves. It is, in effect, a separate constant frequency carrier channel allocated between certain speech channels in each transmission group.

The operation of the pilot is relatively simple. At each repeater point and receiving terminal there appears a meter for registering the output level of the amplifier. The pointer of the meter is expected normally to rest on the zero or normal level layout of the system. If a change in the attenuation of the line circuit causes a departure in the transmission level, the meter reading shows a corresponding "up" or "down" indication and by adjustments of the repeater or terminal amplifier potentiometers the level may be returned to normal. An alarm circuit is furthermore provided at the receiving terminal so that when the level has departed by more than a predetermined amount, say ± 1.5 TU, from the desired normal, the operating attendant is called in to make the adjustment.

A high-frequency current of constant amplitude is transmitted from each end, and the meter indications are measurements of this current at the output of repeater amplifiers, and at the receiving terminal amplifiers (see Fig. 2). A separate pilot frequency is utilized for each direction of transmission. Because no communication is carried on over this pilot carrier current, the band provided is extremely narrow, and no appreciable portion of the frequency spectrum is sacrificed.

The frequency selected for the pilot channel must coordinate with the other carrier system frequencies. The two frequency allocations of the type *C* system require different pilot channel frequencies because their speech channels occupy different frequency bands. The apparatus has therefore been made so that the frequency of the pilot current can be adjusted to any value desired in the carrier range. The frequency selected for a given system may be determined by local conditions of cross-talk or interference, although in general the preferable location is between the channel bands as noted in Fig. 5. The amount of current which is used is limited by its interfering effect into adjacent channels or into other carrier systems on the same line, and it is ordinarily of a low value, of the order of 2 to 6 milliamperes on the line.

Fig. 8 shows schematically the principal features of the terminal pilot-channel circuit as a whole. The oscillator at each transmitting terminal which produces the pilot current is connected to the carrier circuit at the input to the transmitting amplifier, in parallel with the band filters. This current is amplified with the speech currents and transmitted through the directional filter to the line. The attenuated pilot and sideband currents pass from the first section of the line into the receiving directional filter of the first repeater and enter the amplifier. The pilot channel indicator circuit is bridged across the output of the amplifier, and is tuned to

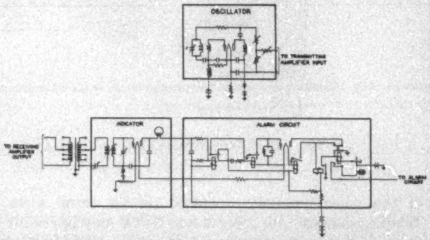
OSCILLATOR
TO TRANSMITTING AMPLIFIER INPUT
INDICATOR
ALARM CIRCUIT
TO RECEIVING AMPLIFIER OUTPUT
TO ALARM CIRCUIT

Fig. 8—Schematic of Pilot Channel Circuits. (The Alarm Circuit is used with Terminals Only)

discriminate very sharply against all but current of the pilot frequency. This circuit has a high impedance relative to the line, so that only a very small percentage of the pilot current is drawn from the line at a repeater point. The remainder is transmitted through the outgoing directional filter and over the subsequent section of the line.

That portion of the pilot current which enters the indicator circuit is amplified and rectified in the vacuum tube detector, and the output current is read on a d-c. milliammeter. As stated above this meter is calibrated to read in TU above and below a mid-scale position which represents a normal transmission level to which the system is initially adjusted.

Entering the receiving terminal of the carrier system, the pilot and speech currents pass through the directional filter and are amplified. As at the repeater, the pilot indicator circuit is bridged across the output of the amplifier. At this terminal, in addition to showing level, the output of the indicator actuates an alarm circuit which operates when the transmission level at this point varies from normal for a set interval of time by more than a prescribed amount. This delay action in the operation of the alarm provides selectivity against slight interference into the pilot channel from currents on the other channels of the system and thereby insures that the alarm indicates a definite level change.

The pilot channel thus insures that the high frequency portion of the system is continuously checked with the exception of the individual channel band filters and modulator and demodulator units. These, however, are particularly stable in operation and require no unusual attention in maintenance. Of course, the over-all check is made at only the pilot frequency in each direction. Variations of line equivalent caused by weather changes increase in magnitude with frequency. Therefore, corrections must be made in the gain relations of the individual channels whenever these weather changes are great. Fortunately the corrections follow a fairly definite relation with variations of pilot level and are ordinarily made by the terminal attendants on the channel potentiometers controlling the demodulator gain by reference to a table. This table shows the relations between the required gain changes at the three channel frequencies in terms of changes at the pilot frequency.

The type of oscillator is essentially the same as that used in the type *C* carrier systems for producing the carrier frequencies. It is controlled by condensers which include an adjustable air condenser for tuning to the particular frequency desired.

Two indicators are located at the repeater, one for each direction of transmission. Each indicator circuit consists of a vacuum tube rectifier operating from coupled tuned circuits into a d-c. milliammeter having a special scale calibrated in transmission units. The filament and plate currents and bias potentials are obtained from the standard 130-volt battery. The advantage of using the same battery for the several functions is that it makes possible the stabilization of the rectifier output with power variations. An adjustable grid bias voltage is obtained from the negative drop of the filament circuit with an opposing 3-volt dry cell battery connected in series. With this arrangement normal variations in the 130-volt source cause only a negligible change in the indicator meter readings.

At the receiving terminal, in addition to the indicator circuit which is the same as at the repeater, an alarm circuit is provided as noted above. A sensitive marginal relay is connected in series with the indicator meter. When this relay operates, it starts the delay circuit by removing ground from the grid condensers of the alarm tube. The leakage through the grid resistances then causes the condenser potential, which is the grid potential of an auxiliary rectifier tube operating from the same power source, to decrease slowly, resulting eventually in a rise in the current of the plate circuit of the alarm rectifier tube. If the marginal relay remains operated for a given length of time, the alarm tube plate current will rise to a value necessary to operate the alarm relays. For shorter periods of operation the normal highly negative grid potential of the rectifier tube is restored and no alarm is operated. The timing of the delay circuit is adjusted by the values of the grid leak resistances and condensers. A delay of about 15 sec. is usually employed which effectually prevents false operation due to occasional transients such as speech interference. The adjustment of the contacts on the alarm relay is ordinarily such as to cause an alarm to be given at limits of ± 1.5 TU variation.

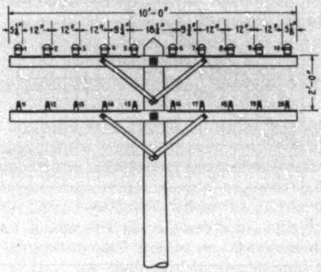

Fig. 9—Showing Arrangement of Wires on Telephone Pole Line

### General Transmission Considerations

*Lines.* The typical open-wire telephone line consists of a number of 10-ft. crossarms spaced two ft. apart on poles whose height varies from 30 ft. upward depending on local conditions. The poles are spaced at an average interval of 130 ft. Each crossarm carries 10 wires. The wires are normally spaced at 12-in. intervals, except in the case of the so-called pole-pairs which straddle the pole and whose wires are about 18 in. apart. (See Fig. 9.) The construction includes pins and glass insulators for supporting the wires.

There are three gages of wire in common use in the telephone plant, having diameters of 104, 128, and 165 mi., respectively. The largest gage, 165-mil pairs naturally afford the lowest attenuation and have been generally used in connection with the application of the longer systems. The pairs of this sized conductor are, however, now fairly well used up for carrier purposes and new installations are being made more often on the smaller diameter circuits.

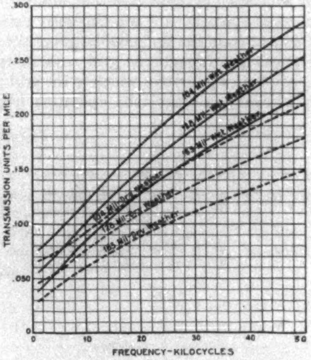

Fig. 10—Attenuation Curves for Open-Wire Lines of Different Gages at High Frequencies

Typical attenuation curves for the three gages of wire and the extremes of weather conditions are given in Fig. 10. It will be noted that the wet weather attenuation may be as much as 40 per cent higher than the dry weather attenuation. These variations are greater at the higher frequencies.

It is interesting in this connection to consider the effect of the possible variation in a practical case. Take, for example, a 165-mil pair 200 mi. long with a carrier channel frequency at 25 kilocycles. This means a total attenuation of 20 T U in dry weather and 29 T U in extremely wet weather, a variation of 9 TU or a current ratio of about 3 to 1. In the case of a still longer line these possible variations present rather startling figures. For example, in a 1000-mi. circuit the variation would be five times the above or 45 TU, which would mean that if the circuit were set up to have a proper volume of transmission in dry weather and rain occurred over the whole line it would cause the speech at the receiving end to drop to but 1/180 of the desired volume if the proper readjustments of gain at the repeaters and terminals were not made. Fortunately, these line variations occur gradually, at least in the case of the longer lines.

In connection with most carrier installations measurements are made[4] of line characteristics prior to the installation of the apparatus. An interesting picture is presented in Fig. 11 which shows the attenuation variations with time on a particular line (about 110 mi. in length) during the period in which a storm arose to cause the attenuation to increase. Later, when the insulators had dried off, the corresponding drop in attenuation is evident. From these variations it is quite obvious that means such as afforded by the pilot channel are needed to insure that the talking circuits provided by the carrier channels remain at substantially constant volume.

In addition to the improvement in stability effected by the use of pilot channel apparatus, substantial advances have been made in the design and application of special types of line insulators in which the high-frequency losses, particularly in wet weather, have been appreciably reduced resulting in still further improvement in stability. The attenuation data given above are for the lines equipped with the older standard types of telephone insulators, which are still employed on the majority of circuits in the telephone plant. However, the newer types of improved insulators are now being applied and their use makes it possible to reduce the wet to dry weather attenuation variation by a factor of about 3 to 1 and to reduce the absolute value of attenuation at the higher frequencies by as much as 25 per cent. Further information describing the development work which has made possible these improved insulators will be made available at a later date.

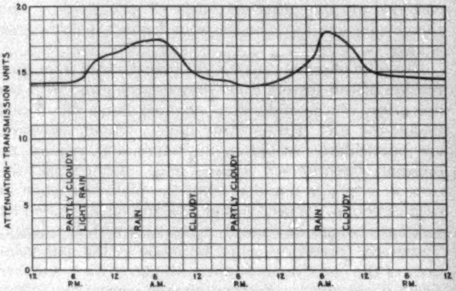

Fig. 11—Variations in Attenuation of a Particular Open-Wire Circuit

While the circuits employed for the transmission of carrier telephone systems as noted above, are largely of open-wire construction, where these circuits pass through the more populated districts of the country it is frequently necessary to insert sections of cable. The smaller closely spaced wires of cables make the problem of attenuation at high frequencies more serious, even where the cables are relatively short, say a mile or so in length. Typical attenuation curves of non-loaded cable pairs are shown in Fig. 12.

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[4] *High-Frequency Measurements of Communication Lines*, H. A. Affel and J. T. O'Leary, A. I. E. E. Transactions, Vol. XLVI, 1927, p. 504.

This situation has led to the development of a special type of cable loading which permits making a substantial reduction in the attenuation for the higher frequencies and which also makes the characteristic impedance of the cable circuit more closely simulate that of the open-wire circuit so that the reflection effects discussed in detail later are thus greatly reduced. This is important, for, whereas the open-wire circuit characteristic impedance varies from 600 to 700 ohms, the non-loaded cable impedance is of the order of 130 to 150 ohms and the reflection losses and also certain resultant cross-talk effects as discussed later are therefore very substantial for even short lengths of non-loaded cable. The present standard types of carrier cable loading systems[5] provide for the use of loading coils spaced at intervals of approximately 930 ft. When loaded, the cable circuits have a characteristic impedance loosely approximating the open-wire impedance over the frequency range used in carrier transmission. This same carrier loading also greatly improves the characteristics of the voice circuit. The high-frequency attenuation is reduced to approximately one-half the non-loaded condition. A special type of cable loading is also available for use in improving the transmission characteristics of office cable and wiring and very short intermediate and entrance cable.

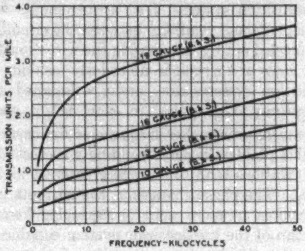

FIG. 12—ATTENUATION OF NON-LOADED CABLE CIRCUITS

*External Interference.* The carrier channels are unusually free from noise due to extraneous induced currents. This, however, is the result of attention to this factor in the design of the apparatus and in laying out the installations rather than anything inherent in the high-frequency feature as such. Our experience has indicated that it is possible, if care is not taken, to have interference from the following external sources:

a. Harmonics of power frequencies.

b. Irregular frequencies produced by abnormal power line actions, such as arcing insulators, charging lightning arresters of certain types, electric railways, series street lighting, etc.

c. Power line carrier systems.

d. Powerful transoceanic radio transmitters.

e. Lightning and other atmospheric disturbances.

In the matter of harmonics of the power line frequencies, the source of their generation normally limits them to very low magnitudes in the high-frequency range which has been employed for carrier systems on telephone lines. In this respect the carrier systems are, in general, affected to a lesser extent than the normal telephone circuits in the voice range. In the latter case, the power circuit harmonics frequently present serious interference problems because the harmonics in the power circuits are substantially greater at the lower frequencies.

Under particular conditions, however, such as, for example, in connection with a series street lighting system operated with individual series transformers or auto-transformers, where a burned out lamp causes the saturation of the transformer magnetic circuit, induced harmonics of considerable magnitude, up to 30,000 cycles and over, have been measured in the carrier telephone circuits. Under the same conditions, however, much larger harmonics are present in the voice-frequency range, so that the induction in the normal telephone circuit is more severe than the carrier circuit.

A much more severe source of carrier interference has been found to result from the abnormal actions of power line circuits in which arcing phenomena occur. Interference of this sort has been noted and traced to such sources as arcing insulators, tree leaks, pantograph and trolley collector sparking, charging lightning arresters, unusual commutator or slip-ring sparking, switching, etc. In the early days of operation of carrier systems, interference of this type formed a not uncommon source of disturbance. The situation was remedied in some cases by cooperation with the power companies concerned. On the whole, this source of interference has been greatly reduced in the past few years.

On occasions the carrier telephone systems have been interfered with by power line carrier systems operating on near-by power lines. Considering the wide-spread use of power line carrier telephone systems and the fact that they normally involve a transmitting power many times that of the systems described in this paper, this would, no doubt, be a more common source of difficulty were it not for the fact that such power systems adjacent to the telephone systems are operated well above the frequency range of the telephone line carrier systems.

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[5] Thomas Shaw and Wm. Fondiller, "Development and Application of Loading for Telephone Circuits," *Bell System Tech. Jl.*, April 1926, pp. 221-281.

Energy picked up from the high-power transoceanic radio telegraph stations, transmitting at frequencies in the carrier range, is an occasional source of interference, particularly in the East where carrier systems are located relatively close to the radio stations. The open-wire telephone lines act as long-wave antennas and intercept the radio energy. This, of course, enters initially on the longitudinal wire circuit to ground. Due to residual line unbalances, some energy is, however, unavoidably passed on to the metallic circuits on which the carrier systems are operated, and enters the speech channel in the form of a tone or note similar to a heterodyne signal at a radio telegraph receiver.

Lightning and general static disturbances form a substantial part of the background noise which is found on all carrier lines. Its general magnitude is ordinarily small, except under certain conditions such as the case of near-by storms.

*Transmission Levels.* In the design and laying out of type *C* installations, the transmission level of a system is ordinarily not permitted to fall below a certain figure, which under particular circumstances might be about − 25 TU, with respect to the transmitting terminal. A transmission level diagram will serve to explain this limitation.

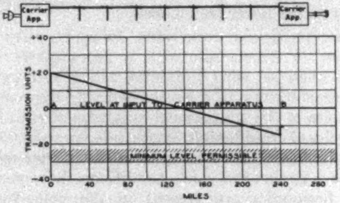

FIG. 13—TRANSMISSION LEVEL DIAGRAM

Let it be assumed that it is desired to effect carrier transmission using a type *C-N* system between points *A* and *B*, 240 mi. apart on 165-mi. conductors. The highest frequency channel is normally considered, which in this case would be 26 kilocycles. The total attenuation of the line at this frequency, as determined from the line attenuation data already presented, would be 35 TU for wet weather conditions of operation. A level diagram would accordingly picture the situation as noted in Fig. 13. At point *A*, sufficient transmitting gain would be provided by the equipment to bring the sending level to + 20 TU. The line attenuation in connection with transmission over the 240-mi. circuit at point *B* would bring the level to − 15 TU. In order to obtain an over-all talking circuit of, say 10 TU, it would be necessary to operate with a receiving gain of 5 TU. It will be noted that in this particular layout the minimum line level is well above the limit set above. In fact, computations would indicate that the line circuit might be extended to the total length of about 300 mi., before the level limits would be exceeded. On longer lines, however, involving many repeater sections, the level limits are raised because of the cumulative effect of noise entering the circuit from a greater number of sources.

The line circuit illustrated is of the simplest type and in a practical case involving sections of intermediate and terminal cable construction, the attenuation would be considerably greater and the effective geographical distance covered for a particular type of apparatus would, therefore, be less.

*Cross-talk.* Telephone circuits which are simultaneously operating in close proximity on a pole line are normally subject to cross-talk because of the mutual inductance and capacity relations between the wires. The problem which this presents in a pole line structure carrying many circuits requires careful consideration, even where the frequencies are no higher than the voice range. The problem is cared for by the application of transposition systems, *i. e.*, arrangements whereby the effect of these relations between the circuits tends to be canceled out by transposing the wires constituting the two sides of a circuit in an orderly fashion. These transposition systems are carefully designed and the transpositions to be applied in each circuit specified.[6]

When using still higher frequencies for carrier purposes, this problem is correspondingly increased as the mutual relations tend to become greater at higher frequencies. The phase changes as the currents progress along the lines are more rapid for the higher frequencies. The design of the transposition system capable of permitting the simultaneous operation of a number of carrier systems on the same pole line is a difficult problem. The subject is one of great complexity and to give it complete consideration would require more space than is available here. It may be noted, however, that, by means of special transposition layouts installed in the circuits being used for carrier transmission, successful operation is being obtained with a large number of carrier systems on the same pole line, both telephone and telegraph. The locations of transpositions in circuits used for carrier transmission occur more frequently than in circuits restricted to operation at voice frequencies, in some cases as frequently as every other pole.

Several factors in the apparatus design have contributed in lessening the degree of hardship imposed by the cross-talk problem:

1. The standardization of arrangements whereby the same frequencies are only employed in a given direction on systems on the same pole line.

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[6] H. S. Osborne, *The Design of Transpositions for Parallel Power and Telephone Circuits*, A. I. E. E. TRANSACTIONS, Vol. XXXVII, 1918, p. 897.

2. The equalization of the transmission levels between paralleling systems.
3. The use of "staggered" frequency allocations for systems in closest proximity.
4. A careful consideration of impedance relations in the line circuits and apparatus.

*Frequency Directions.* The importance of the use of a separate frequency for each direction of transmission may be considered by reference to Fig. 14. If there are two paralleling telephone circuits employing frequencies $f_1$ in the same range, and if there exists between the two circuits a certain amount of cross-talk, when there is a talker at the terminal of one system (No. 1) and a listener at the same terminal of the other system (No. 2), then the speech from the talker at the high level will enter directly into the sensitive receiving circuit of the listener. This is commonly called "near-end" cross-talk. In the case of a carrier circuit, the transmitting terminal would involve a certain amount of amplification. The receiving circuit would likewise, so that the net effect would be that the cross-talk between the two circuits would be amplified by the combined amount of gain or amplification present in the sending and receiving circuits. In telephone parlance it would be stated that this is a situation in which substantial level differences exist between the two circuits.

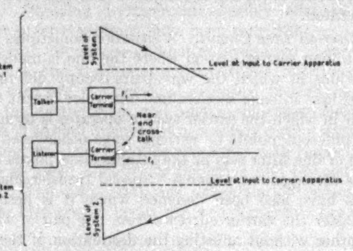


FIG. 14—DIAGRAM ILLUSTRATING OCCURRENCE OF NEAR-END CROSS-TALK BETWEEN CARRIER SYSTEMS EMPLOYING THE SAME FREQUENCY FOR OPPOSITE DIRECTIONS OF TRANSMISSION

On the other hand, in the case of two adjacent carrier systems employing the same frequencies for the same direction of transmission, a cross-talk situation involving only "far-end" cross-talk would exist, as illustrated in Fig. 15. This assumes that near-end cross-talk by reflection as discussed later has been eliminated. In this case the talker and the listener would be situated at opposite terminals of the paralleling circuits and the cross-talk, while being amplified like the near-end cross-talk by the total gain in the transmitting and receiving circuits, suffers the attenuation of the line circuit which more than offsets the amplification. This is, therefore, a very substantial factor in favor of the two-frequency method of operation.

At the carrier frequencies, it has been found impracticable to design transposition arrangements providing for systems where the same frequencies are transmitted in opposite directions. It has been found that, while the two-frequency operation may mean fewer two-way operating channels within the same frequency range on a single pair of wires than would be the case if the same frequency bands were provided for opposite directional transmission, the net result in the former case is to make it possible to obtain a greater number of channels on a pole line having many pairs of wires. The need for the directional coordination of frequencies has led to the general adoption of rules throughout the Bell System whereby the systems are all installed so that the low-frequency directional group of channel transmits east to west or north to south and the high, frequency directional group in the reverse direction, west to east or south to north.

*Level Equalization.* A situation involving an exaggeration of the crosstalk between two paralleling carrier systems may, of course, arise, even in the case of systems involving the transmission of the same frequency in the same direction for the two systems, if the transmission levels of the systems are not the same. If, for example, two systems operating between the same terminals are set up to have the same over-all talking equivalent, and one system has a transmitting gain 10 TU higher than the other, the second system must have 10 TU greater receiving gain in order to provide the same over-all equivalent. This would mean that this system would receive from the first system 10 TU higher crosstalk than if the levels of the two systems were alike. Efforts are therefore made in "lining up" the paralleling systems on a pole line so that as nearly as possible the same level relations are obtained for all systems, and the crosstalk tendencies are thus minimized.

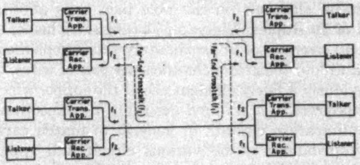
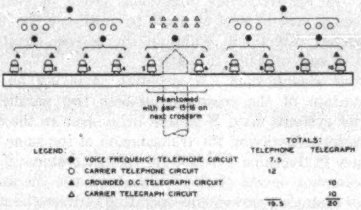


FIG. 15—DIAGRAM ILLUSTRATING OCCURRENCE OF FAR-END CROSS-TALK ONLY IN CARRIER SYSTEMS EMPLOYING DIFFERENT FREQUENCIES FOR OPPOSITE DIRECTIONS OF TRANSMISSION

*Staggering of Frequency Bands.* A substantial reduction of cross-talk is obtained through the staggering of adjacent system frequency allocation as previously noted. Fig. 5 has shown the frequency allocations of the *C–N* and *C–S* systems. Because present standard types of telephone transmitters and receivers have response characteristics which exhibit the greatest sensitivity in the vicinity of 1000 cycles, as the bands of two adjacent channels are shifted from an overlapping position, the cross-talk is appreciably reduced. In this case, also, the overlapping cross-talking points are always opposite sidebands and the intelligibility is completely lost even in the case of a substantial overlapping.

It is customary to install *C–N* and *C–S* systems on the two side circuits of a phantom group. The phantom group comprises four wires which are most closely associated electrically because they are employed not only to provide a telephone circuit on each pair of wires but a phantom telephone circuit each side of which is comprised of one pair of wires in parallel.

A typical arrangement of facilities afforded by one crossarm of the telephone line is illustrated by Fig. 16. It will be noted that this crossarm provides a total of twelve carrier telephone channels, five regular telephone circuits, two and one-half phantom circuits, thus making a total of 19½ telephone circuits. The telegraph facilities would total ten regular grounded d-c. telegraph circuits, one for each wire, and ten carrier telegraph channels on the pole pair, thus affording a total of 20 duplex telegraph channels. This is, therefore, an average of approximately four telephone channels and four telegraph channels per pair of wires, which is obviously a fairly efficient use of the copper wire.


1
2
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10
Phantomed with pair 15-16 on next crossarm
TOTALS:
LEGEND:
TELEPHONE
TELEGRAPH
● VOICE FREQUENCY TELEPHONE CIRCUIT
7.5
○ CARRIER TELEPHONE CIRCUIT
12
▲ GROUNDED D.C. TELEGRAPH CIRCUIT
10
△ CARRIER TELEGRAPH CIRCUIT
10
19.5
20

FIG. 16—ARRANGEMENT OF COMMUNICATION FACILITIES ON ONE CROSSARM

*Impedance.* It is found desirable in connection with communication circuits in general to match carefully the impedances of the various circuit and apparatus components if for no other reason than to insure the best transmission by keeping the reflection losses at a minimum. In connection with carrier systems the matter of crosstalk constitutes an additional important reason for doing this. As noted above, the cross-talk situation is simplified by the standardization of frequency arrangements by which only far-end cross-talk is normally received. This not only reduces the level differences at which cross-talk takes place as explained, but it simplifies the transposition design problem because near-end cross-talk is normally greater in magnitude than the far-end cross-talk. However, if the line circuit is irregular, *i. e.*, if there are abrupt impedance differences in the circuit as it passes from point to point, which bring about wave reflections, these may result in near-end cross-talk being reflected and appearing as far-end cross-talk, thus adding to the true far-end cross-talk and making it more difficult to keep within desirable limits. For this reason every effort is made in the layout of the carrier lines to avoid such reflection effects. This makes it desirable to load even relatively short cables including office cables and wiring. The apparatus terminal impedances are also carefully designed so that their values simulate the characteristic impedance of the line circuits over which the systems are operated.

*Over-all Line Circuit.* A situation sometimes occurs in a long carrier system where the line is made up of sections in which the wire pairs occupy different pin positions in each section, and the voice circuit on the pair in which the carrier system operates is terminated at different points or perhaps joins other lines. The use of line filter sets at the intermediate points makes this arrangement possible. Special transfer line filter sets have also been designed where it is desired to transfer the carrier currents from one pair of wires to another without affecting the destination of the voice circuits and with a minimum impedance irregularity for either circuit. These line filters are sometimes mounted on poles so that this transfer may take place where lines join at an outside point and where office equipment cannot be installed. A circuit arrangement illustrating the use of the pole-mounted high-pass transfer filter set is shown in Fig. 17.

## EQUIPMENT PROBLEMS AND TYPICAL INSTALLATIONS

The increasing use of carrier telephony as a substitute for line construction in providing toll facilities on long circuits has, like the development of toll cables, resulted in further increasing the proportion of the plant investment represented by the equipment within the offices. It has likewise required that a greater part of the maintenance effort involved in taking care of a given number of facilities be devoted to the equipment. These factors have made the design and arrangement of the carrier equipment matters of considerable importance. Recent developments in these respects have, therefore, been directed toward obtaining a high degree of adaptability of the carrier equipment to practical use in the telephone plant. Economies in

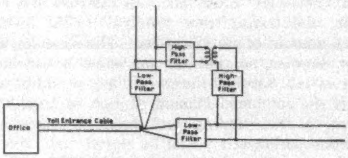

FIG. 17—SCHEMATIC OF HIGH-PASS TRANSFER LINE FILTER CIRCUIT

design have also resulted which have been an important factor in extending the usefulness of the equipment.

The type *C* carrier telephone equipment is mounted on panels employing a uniform dimensional system in a manner similar to the other recent telephone developments. Arrangements have been devised so that in the future this mounting method will permit the desired close association between the carrier filters and other related apparatus in the lines in order to minimize high-frequency losses and impedance unbalances within the offices. Signaling arrangements flexibly adapted to present plant conditions have been provided.

The high frequencies and power levels used in carrier telephony, and the frequency conversion functions of the system are the principal electrical factors which affect the arrangement and amount of equipment involved. The high frequencies necessitate careful wiring, shielding, and location of certain units with respect to others to avoid undesirable inductive and impedance effects. The modulation and demodulation processes and the high energy levels required necessitate the use of numerous vacuum tubes, with the consequent need of suitable sources of power.

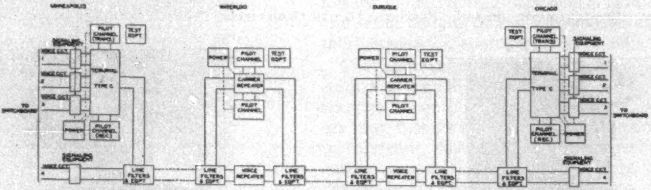

FIG. 18—ELEMENTARY DIAGRAM SHOWING PRINCIPAL EQUIPMENT GROUPS IN TYPICAL TYPE *C* CARRIER TELEPHONE SYSTEM

*Typical System Equipments.* As noted previously, a long carrier telephone system involves equipment at a number of intermediate repeater stations in addition to that at the terminals. Fig. 18 shows the principal equipment groups involved in a typical long carrier system. The particular system illustrated is one of those between Minneapolis and Chicago, with repeater stations at Waterloo and Dubuque, Iowa. The carrier repeater equipment is ordinarily additional to voice-frequency repeater apparatus used in the wire line as mentioned above and is connected so that the high-frequency currents for the carrier pass around the voice-frequency repeater. The wires concerned are employed also for d-c. telegraphy by the use of composite sets.

The principal groups of equipment involved in such a system include the carrier sending and receiving equipment and filters at the terminals, the repeater amplifiers and filters at the intermediate stations, and the line equipment and pilot channel equipment at all points. In addition, power supply equipment and testing equipment are required at all points, and voice-frequency and signaling apparatus at the terminals.

The total amount of equipment involved in a typical carrier telephone system shown in Fig. 18, exclusive of the power supply, includes altogether about 188 panels assembled on racks equivalent to 14 bays[7] and occupying a total floor space, including aisle space, of about 84 sq. ft. If the three channels which the system ordinarily provides were obtained by regular wire circuits, the office equipment might amount altogether to about 36 panels and 1.7 bays, occupying about 10 sq. ft. Thus, in a typical case, about eight times as much office equipment, other than that for the power supply, might be required to furnish a given number of facilities by carrier telephony, in comparison with that needed for the equivalent number of ordinary wire circuits.

*Terminal Station Installations.* The principal equipment groups comprising a terminal of a type *C* system are indicated in Fig. 19. A typical assembly showing a majority of these equipment groups is given in Fig. 20. This does not include the signaling equipment, the pilot channel, or the power equipment. A rear view of this same assembly is shown in Fig. 21.

Returning to Fig. 20, the right-hand bay contains the apparatus comprising two channel terminals. The middle bay includes the third channel apparatus, and the terminal transmitting and receiving amplifiers and directional filters which are mounted in the upper portion. The box-like units on both bays are the band filters and directional filters. On the right-hand bay the upper of the panels with three vacuum tubes is the modulator-oscillator panel of one channel. Below it is the demodulator-oscillator panel of the same channel. Below the latter and in the center of the bay is the jack mounting strip which makes it possible to disconnect, or switch for testing purposes, the various units of the complete equipment. The demodulator-oscillator panel and modulator-oscillator panel, respectively, are the next two panels of the second channel. The terminal strips will be seen at the top of the bays. The metal shields surrounding the vacuum tubes are useful for mechanical protection only. The testing and power distribution equipment is located in the left-hand bay.

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[7] A bay consists of two channel or I-beam uprights, ordinarily about 11½ ft. high, and spaced so as to mount unit panels 19 in. wide and of varying height.

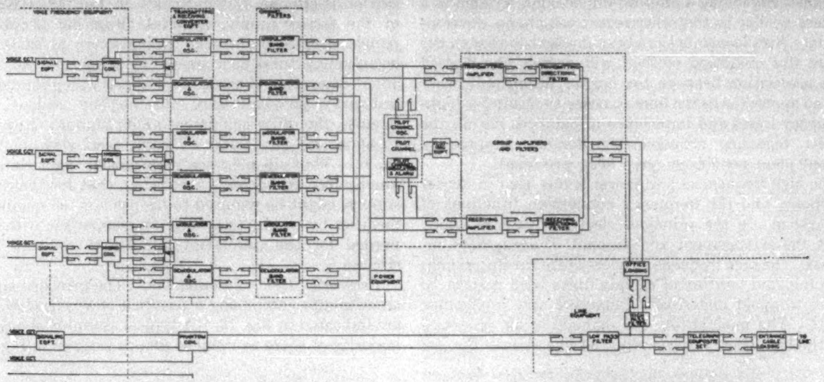
VOICE FREQUENCY EQUIPMENT
TRANSMITTING & RECEIVING CONVERTER EQPT
CHANNEL FILTERS
VOICE CCT
SIGNAL EQPT
HYBRID COIL
NET
MODULATOR & OSC.
DEMODULATOR & OSC.
MODULATOR BAND FILTER
DEMODULATOR BAND FILTER
PILOT CHANNEL OSC.
PILOT CHANNEL
& ALARM
TEST EQPT
TRANSMITTING AMPLIFIER
TRANSMITTING DIRECTIONAL FILTER
GROUP AMPLIFIERS AND FILTERS
RECEIVING AMPLIFIER
RECEIVING DIRECTIONAL FILTER
POWER EQUIPMENT
OFFICE LOADING
LINE EQUIPMENT
HIGH PASS FILTER
SIGNALING EQPT
PHANTOM COIL
LOW PASS FILTER
TELEGRAPH COMPOSITE SET
ENTRANCE CABLE LOADING
TO LINE

Fig. 19—Schematic showing Principal Units Comprising Type *C* Terminal Equipment

Fig. 20—Type *C* Carrier Telephone Terminal Equipment, Typical Assembly of System. (Front)

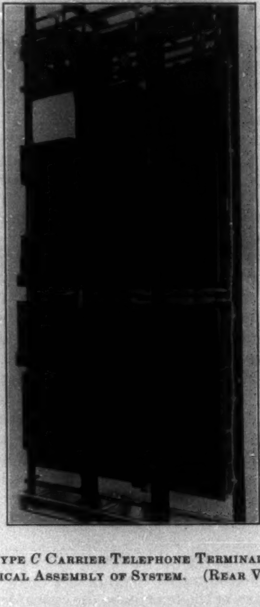

Fig. 21—Type *C* Carrier Telephone Terminal Equipment, Typical Assembly of System. (Rear View)

The pilot channel apparatus at the terminal station, which is employed in regulating the performance of the system to compensate for variations in the line equivalents, is assembled in a typical installation as shown in Fig. 22. This apparatus may be located adjacent to the carrier terminal apparatus. The upper panel is the indicator unit with the indicator meter shown in the upper center of the panel. The panel immediately below this is the alarm panel with its voltmeter relay.

On both of these panels the associated vacuum tubes are mounted in the rear. The lowest panel is the oscillator panel with its vacuum tube and frequency control.

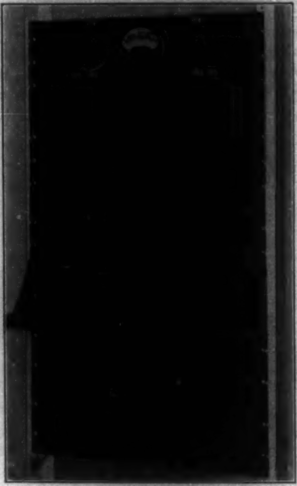

Fig. 22—Typical Assembly of Pilot Channel Equipment in Terminal Installation

*Typical Repeater Station Installations.* The equipment at each carrier repeater station consists mainly of the units indicated in Fig. 23. It is seen from this figure that the principal items are the line filter equipment, the amplifiers, the equalizers, the directional filters, and the jacks provided for testing and patching the equipment. Pilot channel equipment, power supply equipment, and testing equipment are also included. The amplifier equipment in each carrier repeater, other than the 15 TU auxiliary amplifier, is identical with the group amplifiers employed in each terminal station. The filters are also identical in type excepting that twice as many directional filters are required at each repeater station as at each terminal.

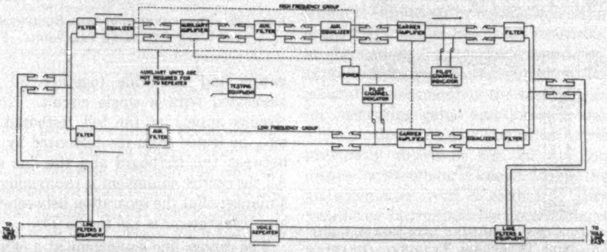
HIGH FREQUENCY GROUP
FILTER
EQUALIZER
AUXILIARY AMPLIFIER
AUX. FILTER
AUX. EQUALIZER
CARRIER AMPLIFIER
FILTER
AUXILIARY UNITS ARE NOT REQUIRED FOR 30 TU REPEATERS
TESTING EQUIPMENT
POWER
PILOT CHANNEL INDICATOR
PILOT CHANNEL INDICATOR
LOW FREQUENCY GROUP
FILTER
AUX. FILTER
CARRIER AMPLIFIER
EQUALIZER
FILTER
TO TOLL WEST
LINE FILTERS & EQUIPMENT
VOICE REPEATER
LINE FILTERS & EQUIPMENT
TO TOLL EAST

Fig. 23—Schematic showing Principal Equipment Unit in Carrier Repeater Circuit

A typical complete installation of two carrier repeaters with testing and battery supply circuits located in the bay at the left is shown in Fig. 24. The bottom panel on the left-hand bay is a reserve amplifier. Above this panel are the filament rheostats, telegraph instruments, jack panels, key panels for controlling the power supply, a panel containing a thermocouple and meter for testing, meters for reading currents and voltages, and finally the alarm relays. These last are operated by failure in the plate current in the amplifier tubes, thereby indicating when a tube burns out, or failure of either A or B battery supply.

Each repeater bay in this case, Fig. 24, contains an auxiliary amplifier to increase the gain in the high-frequency group. From top to bottom the panels are input filters, auxiliary filters, equalizers, auxiliary amplifier, two regular amplifiers separated by a jack panel, and output filters. The arrangement of filters and equalizers is chosen to minimize any tendency toward inductive feed-back effects between the output and input circuits of any one repeater as well as cross-talk between different repeaters on adjacent bays.

The pilot channel equipment at a carrier repeater station is similar to that employed at the terminal stations, excepting that the alarm and oscillator panels are not included. The alarm apparatus is omitted in this case, since it is not the practise to have the carrier repeater attendants readjust the carrier repeaters to take account of line changes, excepting when instructed to do so by the attendants at the terminal stations where the alarm apparatus is installed. The pilot channel equipment at each repeater station thus consists principally of an indicator panel associated with the transmission circuit in each direction, which is assembled with the other equipment as previously shown at the extreme right in Fig. 24.

*Line Equipment.* Fig. 25 shows the principal line equipment units which are closely associated in effecting connection between the high-frequency circuit of the carrier system and the voice-frequency line. This equipment consisting of the line filters, composite sets, and entrance and office load coils is mounted together in one assembly and located as near as practicable to the other carrier equipment. A method of assembly which is now under development is shown in Fig. 26. The bay shown contains the line equipment for two phantom groups.

FIG. 24—TYPICAL INSTALLATION OF CARRIER TELEPHONE REPEATER EQUIPMENT. (FRONT VIEW)

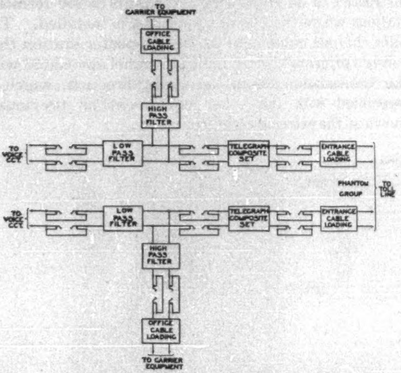
TO CARRIER EQUIPMENT
OFFICE CABLE LOADING
HIGH PASS FILTER
TO VOICE CCT.
LOW PASS FILTER
TELEGRAPH COMPOSITE SET
ENTRANCE CABLE LOADING
PHANTOM GROUP
TO TOLL LINE
TO VOICE CCT.
LOW PASS FILTER
TELEGRAPH COMPOSITE SET
ENTRANCE CABLE LOADING
HIGH PASS FILTER
OFFICE CABLE LOADING
TO CARRIER EQUIPMENT

FIG. 25—SCHEMATIC CIRCUIT SHOWING LINE FILTER EQUIPMENT FOR TYPE *C* CARRIER TELEPHONE TERMINAL. (PHANTOM GROUP)

This compact method of assembling and wiring the line equipment reduces the amount of office cabling required for the carrier and therefore reduces the possibility of inter-system cross-talk between carrier systems within the same office. The cross-talk requirements in an office may be more severe than on the pole lines because the level difference between circuits which operate on different pole lines terminating at the same office may be as much as 50 TU. As an aid in obtaining the required electrical separation all high-frequency wiring is reduced to a minimum by segregating and mounting together all line equipment associated with a single circuit. No high-frequency circuits appear at the toll testboard. The toll lines may be tested from the testboard by means of trunks between the testboard and the line equipment bays. All the carrier equipment is thoroughly shielded in such a manner that the separation between the equipment of any two systems is 120 to 135 TU.

FIG. 26—ARRANGEMENT OF LINE EQUIPMENT IN ONE ASSEMBLY FOR TYPE *C* CARRIER TELEPHONE. (FRONT VIEW)

The carrier line equipment at a carrier repeater station is generally similar to that at the terminal stations, as previously shown in Fig. 26. At each repeater station, however, this equipment is provided in the lines in both directions. Two types of low-pass line filters are employed at the repeater station, one adapted to circuits in which both carrier and voice-frequency repeaters are used and the other, which is less commonly used, for circuits employing only carrier repeaters and where the voice circuit continues through without a repeater.

*Voice-Frequency and Signaling Equipment.* The general function of the voice-frequency terminating equipment is to associate by means of a hybrid coil and network, the ordinary two-wire circuits in the telephone switchboard, including both talking and signaling functions, with the sending and receiving branches of each of the different carrier channels. The general arrangement of this equipment in the circuit is shown in further detail in Fig. 27. This includes the signaling equipment and makes provision for the connection of a balancing network.

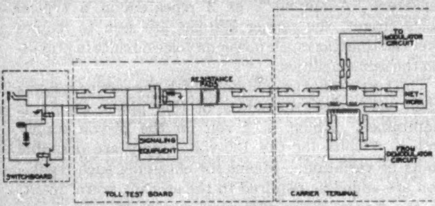
TO MODULATOR CIRCUIT
RESISTANCE PADS
NET-WORK
SIGNALING EQUIPMENT
FROM DEMODULATOR CIRCUIT
SWITCHBOARD
TOLL TEST BOARD
CARRIER TERMINAL

FIG. 27—SCHEMATIC OF VOICE-FREQUENCY CIRCUIT FOR TYPE *C* CARRIER TELEPHONE SYSTEM

The use of a two-wire termination for the carrier system is necessary because ordinary telephone circuits at the switchboards, such as trunks, subscribers' lines, etc., are of the two-wire type and the cord circuits for interconnecting these are of this type. Hence, such a termination of the carrier system makes it possible to connect it to other circuits with the same apparatus and in the same manner as with ordinary telephone circuits.

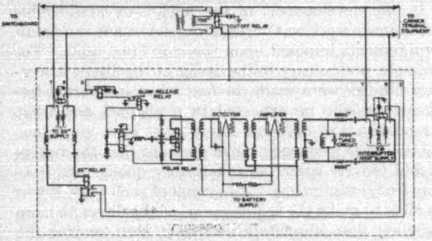
TO SWITCHBOARD
CUT OFF RELAY
TO CARRIER TERMINAL EQUIPMENT
T
R
S
SLOW RELEASE RELAY
TO 20~ SUPPLY
DETECTOR
AMPLIFIER
1000~ TUNED CIRCUIT
TO INTERRUPTED 1000~ SUPPLY
POLAR RELAY
20~ RELAY
TO BATTERY SUPPLY

FIG. 28—SCHEMATIC OF 1000-CYCLE RINGING CIRCUIT

The signaling apparatus consists of a 1000-cycle ringer of the type which is employed on long voice-frequency lines. This is connected to the voice-frequency terminal of the carrier system in the same manner as to other voice circuits. The use of 1000-cycle signaling with the carrier has been desirable in place of the more simple low-frequency signaling apparatus used on shorter lines, since frequencies less than 200 cycles are not efficiently transmitted.

Fig. 28 shows a simplified diagram of this type of ringer. The transmitted signaling currents as impressed upon the carrier channel are of 1000-cycle frequency interrupted at a speed of 20 interruptions per second. This ringing current supply is obtained either from 1000-cycle generators or vacuum tube oscillators. Such currents, while in the voice-frequency range and thus capable of being transmitted readily, form a signal of sufficiently distinctive character to permit separation from ordinary voice currents. Thus, practical freedom from voice interference with the receiving apparatus is obtained, since this apparatus is designed to respond to very small currents of this character but to discriminate sharply against other currents.

*Tests and Adjustments of Apparatus.* For the purpose of testing and "patching" (*i. e.*, interconnecting various equipment units in the carrier system), jacks are provided as previously shown in Fig. 19. The equipment which is employed for testing and adjusting the carrier apparatus provides means for measuring gains and losses at the various frequencies encountered and includes a supply of testing current at these frequencies. The general arrangement of the testing apparatus provided for measuring gains and losses is shown in Fig. 29. This is assembled with the other carrier equipment as previously shown in Fig. 20. It consists chiefly of means for switching a known loss in the testing circuit, an attenuator, and a calibrated thermocouple type measuring instrument for determining the value of the current transmitted through this apparatus. The 1000-cycle current is used for practically all testing of the terminal apparatus.

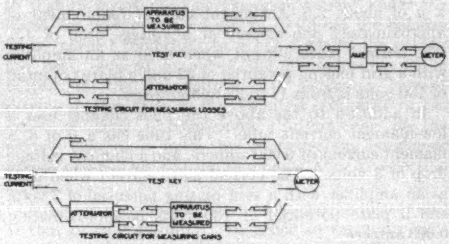
APPARATUS TO BE MEASURED
TESTING CURRENT
TEST KEY
AMP
METER
ATTENUATOR
TESTING CIRCUIT FOR MEASURING LOSSES
TESTING CURRENT
TEST KEY
METER
ATTENUATOR
APPARATUS TO BE MEASURED
TESTING CIRCUIT FOR MEASURING GAINS

FIG. 29—SCHEMATIC OF TESTING CIRCUIT FOR TYPE *C* CARRIER TELEPHONE SYSTEM

The testing equipment at a carrier repeater station is arranged in a manner similar to that at the terminal stations, as previously shown in a general way in Fig. 29. It requires in addition, however, a carrier-frequency oscillator. Only high-frequency currents are transmitted through the carrier repeater, hence the 1000-cycle supply employed at the terminals where modulation and demodulation of these carrier currents occur, is not useful in testing the repeater equipment.

It is customary to make periodic tests of the equipment. On the longer circuits[8] each day the channels are "lined up" for the required over-all transmission equivalents. At less frequent intervals the vacuum tubes are checked for emission, the gains of the sending and receiving branches are measured, the carrier synchronism is checked, etc.

*Vacuum Tubes.* Two principal types of vacuum tubes are employed in this system. One of these is the so-called *L* tube. This tube has a filament circuit requiring a current of approximately 0.5 ampere with a voltage drop of 4.0. It has a $\mu$ of 6.5, and a normal plate current, when used as an amplifier with a *B* voltage of 130 and a *C* biasing potential of 8, of about 6.5 milliamperes.

For the output stage of the amplifier a higher capacity tube is employed. This is a so-called *O* tube having a $\mu$ of about 2.5, a filament current requirement of approximately one ampere at a voltage drop of 4.5. The normal plate current when used as an amplifier with a grid biasing potential of 22 and a plate potential of 130 volts is from 17 to 35 milliamperes.

In addition to the above the pilot channel uses a low-filament current tube. This tube has a $\mu$ of 8, a filament current of 0.060 ampere, and a filament voltage drop of 3 volts. The normal plate current when used as an amplifier with a grid biasing potential of 7 volts and a plate potential of 130 volts is approximately 0.003 ampere.

The tubes employ oxide coated filaments and have been designed to be especially long lived to meet daily 24-hour service requirements.

*Power Supply.* The power required for the carrier equipment is taken from the telephone office supply where this is adequate. Usually the 24-volt central office power plant is suitable for the purpose, and the 130-volt supply for the plate circuits of the tubes is taken from the same batteries provided for telephone repeaters if available. The carrier requirements, however, may amount to a substantial addition to the load on the power plant, particularly where several carrier systems are installed in a relatively small office.

The amount of power required for a typical carrier telephone system is substantially larger than the usual telephone power requirements for the same number of facilities. Each system terminal requires approximately 8 amperes at 24 volts and about 400 milliamperes at 130 volts. The power required for each carrier repeater amounts to about 4 amperes at 24 volts and 250 milliamperes at 130 volts. Thus the total power required for one three-channel system with two intermediate repeater stations would be in the neighborhood of 24 amperes at 24 volts and 1.3 amperes at 130 volts, amounting altogether to about 750 watts. This corresponds roughly to the amount of power consumed by about 80 telephone repeaters, so that the total power required for three such carrier systems would be about equal to that required for a cable repeater station having between 200 and 300 repeaters. Assuming 2 or 3 repeaters in a typical voice circuit, the carrier systems are seen to require over ten times as much power as voice circuits in providing the same facilities.

The best results are obtained with the carrier systems when very close regulation of this power supply is maintained. About ± 1 volt for the 24-volt supply and ± 5 volts for the 130-volt supply are desirable limits of variation. Means for obtaining such regulation are added as required to the existing power plant. In the larger offices this may consist of a duplicate battery with full-floating operation. In the smaller installations, a relay regulating circuit may be added which controls the filament current as the voltage varies from 20 to 28 volts. This consists of a sensitive voltmeter relay arranged with accessory relays to cut resistance in and out of the individual filament supply circuits as the voltage varies.

## DESIGN OF CARRIER APPARATUS

Many will, no doubt, be interested in the further technical details of some of the more important units of the carrier system.

In the development of the apparatus considerable preliminary work was necessary to determine the circuit requirements imposed upon the individual units. For example, preliminary to the design of the filters, laboratory studies were made to find what interfering frequencies might be expected in a channel and what attenuation the different filters must offer at various points in the frequency range, in order that the system should provide speech of satisfactory quality and freedom from interference. As a result of such work, it was possible to make the requirements of the filters no more stringent than absolutely necessary, thus keeping the cost down to a minimum while insuring adequate performance. Preliminary studies were also made on the other parts of the system such as modulator, demodulator, oscillator, etc. In the descriptions which follow, no attempt has been made to describe this preliminary work, the discussion being limited to the requirements imposed, and the circuits devised to meet these requirements.

*Modulator and Transmitting Oscillator.* A circuit drawing of the modulator is shown in Fig. 30. It may be considered that the function of the modulator is to translate the voice frequencies along a frequency scale to some assigned location in the band of frequencies to be occupied by the carrier system. The carrier frequency controls the location of the shifted voice band or sideband, and the oscillator, which provides this frequency, is made an integral part of the modulator unit. The modulating process requires a circuit element having a non-linear response characteristic to produce the sideband from a combination of the carrier and voice frequencies. In this circuit the three-element vacuum tube is operated to give this required characteristic.

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[8] W. H. Harden, "Practises in Telephone Transmission Maintenance Work," *Bell System Tech. Jl.*, Vol. 4, Jan. 1925, p. 26-51.

Since the carrier is not transmitted in the type *C* system, each modulator and demodulator becomes a complete and independent frequency changing unit. As previously noted the frequency stability of each oscillator must be sufficiently good so that the carriers of the corresponding modulator and demodulator units will differ but slightly in frequency so as not to affect unfavorably the speech which is transmitted. In this connection both naturalness of the received speech and intelligibility must be considered. In the type *C* system satisfactory results have been obtained by holding the difference between the carrier frequencies of any two associated units due to all causes to within about 20 cycles.

The usual causes of frequency variation are fluctuations in the A and B battery supply, and changes in temperature and humidity. Vacuum tubes have to be replaced periodically and differences in the tube characteristics may cause a slight variation in the frequency.

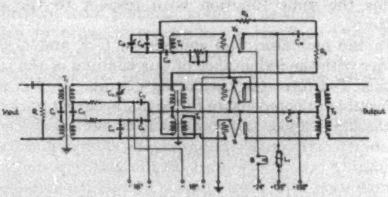

FIG. 30—SCHEMATIC OF MODULATOR CIRCUIT AND TRANSMITTING OSCILLATOR

The type of oscillator circuit was chosen to furnish the greatest frequency stability with variations in power supply, particularly in the plate battery. Fluctuations in the filament current are reduced by the use of ballast resistors to a point where they do not appreciably affect the oscillator frequency.

In order to maintain stability with temperature and humidity changes, it was necessary to develop circuit elements, (primarily the inductance in the oscillating circuit) which were not greatly affected by these variables. As a result the oscillators vary less than 10 cycles per second at the highest carrier frequency with power variations within the limits of plant maintenance, and have a frequency temperature coefficient of approximately 0.002 per cent per deg. fahr. This corresponds to about one cycle per second per deg. fahr. in the highest frequency units used in the type *C* system. The temperature difference between offices containing terminal equipment seldom exceeds 20 deg. fahr.

An extreme change in frequency of 20 cycles per second may be encountered with different tubes. Maintenance experience has shown that it is usually unnecessary to check the synchronization of the modulator and demodulator carrier frequencies more often than once a week, unless tubes are replaced or some other unusual circuit change occurs.

The modulating tubes are placed in a push-pull arrangement, and the carrier voltage is applied to both grids in phase and the suppression of the carrier frequency secured by a differential connection of the output transformer windings. It is difficult to suppress completely the carrier and a limit is set upon the amount which can be allowed on the high-frequency line without causing interference between systems. This limit requires that the carrier flowing out from the modulator should not exceed approximately 500 microamperes. With varying conditions of power, the balance of the modulator cannot be maintained absolutely constant, so that to insure meeting this requirement under the worst conditions it is necessary to adjust the balance under normal conditions to a point where the carrier has been reduced to about 150 microamperes at the output of the modulator. The sideband current flowing at this place in the circuit is ordinarily of the order of 2000 microamperes. Adjustment of the carrier balance is made by changing the condenser across one-half of the input circuit, and by selecting tubes.

A further requirement imposed on the modulator unit is that of gain stability. In order to maintain sufficiently constant transmission over a circuit there must be a high degree of inherent stability in all those units whose variations are not included in the indications of the pilot channel. The modulator and demodulator are the only units in this category.

In the modulator and demodulator the principal factors tending to cause instability of gain are the variations in plate and filament battery where these occur and changes in the tubes during their life. A characteristic behavior of the modulator described below has been used to advantage in minimizing this instability. The gain of the modulator for varying values of the carrier voltage passes through a maximum near the point where the grids of the modulator tubes are driven to a positive potential, with respect to the filament. The output from the carrier oscillator will increase with increasing plate potential, and due to the above characteristic may be made to compensate somewhat for the tendency of the gain of the modulating tubes to increase. Fig. 31 shows the change in gain of the modulator circuit when the plate potential of either the oscillating or modulating tubes is changed independently. With these arrangements the total variation in the modulator or demodulator gain, due to the fluctuations of power supply, does not usually exceed ± 0.25 TU. The possible variation due to tube differences is somewhat larger, approximately ± 0.7 TU. This is not serious since tubes are ordinarily replaced when a system is out of service, and the gain can be readjusted before the system is restored to operation.

Another requirement which the modulator must meet is one of transmission quality or equality in transmission gain at various frequencies in the voice band. The modulator should not limit the band of frequencies which is to be transmitted over the system. The characteristics of the transformers and the impedance in which the output of the modulator is terminated are the controlling factors in the quality of the modulator. A typical characteristic of modulator gain with frequency under ideal termination is shown in Fig. 32. In the type *C* system the effect of the band filter impedance is to cause a variation in this characteristic of approximately 5 *TU* at 2800 cycles.

The final requirement placed upon the modulator relates to the energy level which must be handled. It should not be possible to overload the modulator seriously with the amount of power produced by a subscriber's set at the transmitting toll testboard level. With a given modulator circuit, this requirement can be met by designing the input transformer with the proper turns ratio.

The following paragraphs give a more detailed description of the actual circuit which has been developed to meet the above requirements.

The voice-frequency circuit is through the hybrid coil to the terminals of the input transformer. The resistance placed across the input circuit is to improve the impedance terminating this branch of the hybrid coil, and thus improve the terminal impedance looking into the hybrid coil from the voice-frequency line. The condenser *C*–1 is inserted in series with the primary winding of the transformer to improve the transmission characteristic of the circuit at low frequency. This condenser resonates with the inductance of the primary winding, increasing the voltage across the primary at low frequencies where the modulator input circuit tends to become less efficient. The two windings of the secondary side of the transformer are separated by bypass condenser *C*–2, as they are at different potentials from ground, due to the series connection of the filaments of the vacuum tubes. The variable condenser *C*–3 affords a means of balancing the carrier-frequency potentials. Condenser *C*–4 is one-half the maximum capacity of *C*–3 in order that carrier frequency unbalance in either side of the circuit may be compensated for to a sufficient degree by means of the one adjustable condenser *C*–3. The voltages, $E_1$ and $E_2$, provide the grid bias for the modulating tubes *V*–1 and *V*–2. The condensers *C*–5 and *C*–6 provide a low impedance path around the source of biasing potentials for the carrier frequency, and condenser *C*–7 in the plate circuit performs the same function with respect to the plate battery.

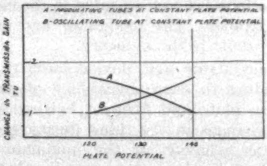

FIG. 31—MODULATOR GAIN—RELATION TO PLATE POTENTIAL

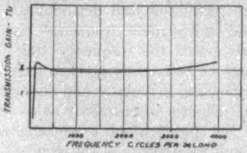

FIG. 32—MODULATOR GAIN—RELATION TO FREQUENCY

In the oscillator, the condensers *C*–8 and *C*–9 together with the inductance of one winding of the transformer *T*–4 form the oscillating circuit. *C*–9 is made adjustable to compensate for manufacturing variations in the inductance, and to provide in addition a certain flexibility in frequency adjustment. A grid bias for the oscillating tube is provided by the grid leak-condenser combination *G*. The plate battery is connected through the retardation coil *L*–1, which presents a high impedance to the carrier frequencies, and prevents their flowing through the plate battery. The carrier current in the plate circuit divides between two paths, one through *R*–2 the feed-back resistance to the grid circuit, and the other through *R*–3, the output resistance, and the transformer *T*–2 which impresses the carrier voltage on the grids of the modulating tubes. The filaments of the tubes in the modulator circuit are wired in series, and the current flow is regulated by a ballast resistor *B*.

Figs. 33 and 34 show the front and rear views of the modulator panel. The adjustable condensers which control the carrier frequency and the carrier balance are accessible from the front of the panel. In the rear view, the oscillator circuit occupies the left-hand side of the picture. The oscillating transformer is in the upper left-hand corner, with the oscillating condensers directly below it. The feed-back and output resistances are connected across the top of the panel. The oscillating tube is left of the three tubes, and the carrier input transformer is below it. The voice input transformer is to the right of the carrier transformer, and the output transformer is located in the upper right-hand corner. A metal cover fits over the complete panel at the back to provide electrical shielding and mechanical protection. All outside connections to the panel are made through the terminal block in the lower right-hand corner. Wires supplying power, together with those which are at a low a-c. potential with respect to ground, are run in a cable, while wires at a high a-c. potential are run directly from point to point in as short a path as possible in order to reduce losses resulting from the capacity of these wires to ground.

Fig. 33—Assembly of Modulator Panel. (Front View)

*Demodulator and Receiving Oscillator*. The circuit of the demodulator shown in Fig. 35 is in many respects similar to that of the modulator. The function performed by the demodulator is also similar, being a translation from a high-frequency band to a lower instead of the reverse.

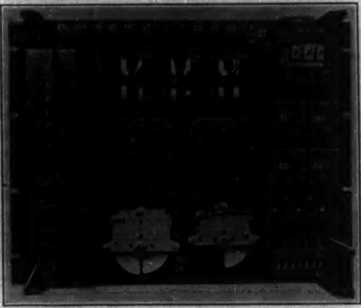

Fig. 34—Assembly of Modulator Panel. (Rear View)

The oscillator which supplies the carrier to the demodulator is of the same type as the modulator oscillator, and has been discussed in connection with that circuit. No adjustable feature for balancing the carrier is required in the demodulator circuit. The carrier suppression needed in addition to the suppression inherent in the balanced circuit is provided by the low-pass filter at the output. If the carrier is not sufficiently suppressed, it will pass into the voice circuit or across the hybrid coil into the associated modulator, causing, in some channels, an objectionable beat tone.

The transmission stability of the demodulator is obtained by the same methods used in the modulator since the performance of the two circuits is similar, and the transmission quality requirement is essentially the same for both units. A typical demodulator characteristic is shown in Fig. 36. This characteristic at the higher frequencies is controlled by the low-pass filter.

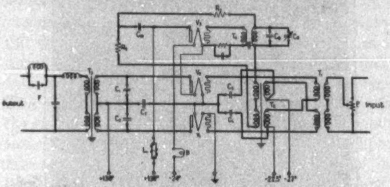

Fig. 35—Schematic of Demodulator Circuit and Receiving Oscillator

One feature which is required with the demodulator, but not with the modulator, is a variable control of the transmission gain of the circuit. Due to the unequalized transmission of the line section adjacent to the terminal, or other differences in the channel equivalents, the three sideband currents normally arrive at a receiving terminal with unequal strength. A potentiometer controlling the gain of the demodulator permits of an equalization of the over-all losses on the three channels.

In the following detailed description of the demodulator circuit, other minor differences between it and the modulator may be pointed out:

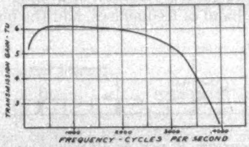

Fig. 36—Demodulator Characteristic—Gain and Frequency

The sideband frequencies enter the demodulator, passing to the potentiometer *P*–1, which controls the amount of current to the input transformer *T*–1. The position of the carrier input transformer *T*–2 is somewhat different in the demodulator circuit as compared to the modulator circuit, due to the difference in the high-frequency characteristic of the *T*–1 transformers. In the modulator, this transformer must be designed primarily to transmit voice frequencies. It has a comparatively large capacity to ground which would reduce the effective carrier voltage on the tube grids if it were placed in the same circuit position as is the demodulator transformer. The function of most of the circuit elements is evident from the previous description of the modulator. The $C$–1 and $C$–2 condensers provide a low-impedance path for the carrier frequency. They are necessary here because the transformer $T$–3 designed for high efficiency at voice frequencies has considerable leakage inductance which would present a high impedance to the carrier in the plate circuit if the condensers were not provided. Of course, for the maximum gain, the impedance of this circuit should be a minimum at carrier and sideband frequencies. At the output, a low-pass filter structure $F$ provides for the suppression of the unwanted products of demodulation.

FIG. 37—ASSEMBLY OF DEMODULATOR PANEL. (FRONT VIEW)

A front view of the demodulator unit is shown in Fig. 37. The panel layout and general appearance is similar to that of the modulator. The two dials shown control the demodulator input and the oscillator frequency, respectively, as indicated in these figures.

*Filters.* The general function of a band filter is the selection of a band of frequencies, and the protection of this band from interfering frequencies located on either side. The filters determine what band width is transmitted, and thus to that extent, they control the quality of speech which may be obtained through the carrier circuit. The type $C$ system transmits a band corresponding to approximately 200 to 2700 cycles per second in the voice range.

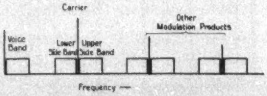

FIG. 38—FREQUENCY RANGE OF PRODUCTS OF MODULATION

In considering the requirements imposed upon the band filters it is necessary to keep in mind[9] the fact that the modulator produces not only the particular sideband which is to be transmitted but also an unwanted sideband of the same volume as the wanted sideband and equal to it in width, located on the opposite side of the carrier frequency. In addition to these products of modulation there are produced other frequency bands, the important ones occupying sideband positions about the harmonics of the carrier frequency. See Fig. 38.

The first requirement on the band filters is imposed by the need of suppressing the unwanted sideband to prevent distortion when the carriers are out of synchronism. The tests mentioned above in connection with the oscillator frequency stability were made with but one sideband transmitted. If both sidebands are transmitted the carriers must be exactly in synchronism or a "wobble" due to the demodulation of both sidebands can be detected. As this carrier difference increases, one sideband must be suppressed by an increasing amount. For a carrier frequency difference of about 20 cycles, it is necessary to suppress the unwanted sideband about 40 TU, thus reducing it to about 1/100 of the strength of the wanted sideband in order to eliminate completely this type of distortion. This requirement can be met by providing the necessary attenuation in either the transmitting or the receiving band filter, or by making the sum of their attenuations equal to 40 TU.

In a multi-channel system in which the transmitted sidebands are close together, the suppression of the unwanted sideband is necessary for another reason. The unwanted sideband from one channel overlaps the wanted sideband of an adjacent channel and would be demodulated and appear as "cross talk" into this channel if it were not suppressed by the transmitting band filter. The suppression needed is determined by the amount of interference which can be tolerated from one channel to another. It has been found that to meet this requirement the transmitting band filter must suppress the unwanted sideband about 60 TU. The other modulation products mentioned above must also be reduced by the transmitting band filter to a value which will not cause interference in any channel into which they might pass. The discrimination requirement for these frequencies is less severe because the magnitude of these modulator products is not so great.

A particular termination is required at the end of the filter which is connected to the modulator. In order to get the maximum sideband power out of the modulator used, the impedance of the associated band filter, seen from the modulator, must be made low over the range of voice frequencies.

With the channels placed close together and coordination of different types of systems depending upon the channel locations, it is important that the band filters remain constant after manufacturing and that all filters of the same type be manufactured to meet close requirements. For proper coordination between systems, it has been found desirable to keep all the channel bands within ± 125 cycles of an assigned location. In the higher frequency channels, this means that the filters must be manufactured to a frequency accuracy of the order of ½ of one per cent.

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[9] R. V. L. Hartley, "Relation of Carrier and Side Bands in Radio Transmission," *Bell System Tech. Jl.*, Vol. 2, April 1923, pp. 90-112.

The attenuation requirements for the receiving band filter are somewhat different from those of the transmitting band filter. The purpose of the receiving band filter is the suppression of the frequencies of the adjacent channels as they are received over the line. In contrast to the transmitting filter, which must suppress the unwanted frequencies produced in its own channel, a filter with somewhat different characteristics could be used, therefore, for a receiving filter. While the requirements were determined separately for the receiving and transmitting filters, it was desirable in the interest of manufacturing economy to build both alike, setting requirements on the basis of a double purpose filter. Thus, this filter had to provide attenuation at each frequency to meet the more severe of the requirements for either the transmitting or the receiving position. Fig. 39 shows the transmitting characteristic of a typical filter designed to meet the requirements outlined above.

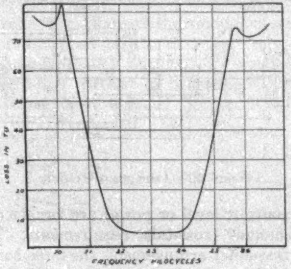

FIG. 39—TYPICAL BAND FILTER CHARACTERISTIC

As has been explained, the grouping of the channel bands in opposite directions requires the use of so-called directional filters at terminal and repeater points These filters occur in the circuit in pairs, each pair consisting of one high-pass and one low-pass filter. The cut-off point of the filters is determined by the type of system in use—*C–S* or *C–N* and its corresponding "grouping point." At repeater points, the filters are split for each direction in order to provide selectivity at both the output and input circuits of the amplifiers.

Considering the closed circuit through the two amplifiers and the four directional filters, the attenuation in this loop must be considerably greater than the sum of the gains of the two amplifiers at all frequencies. In the regions outside of the carrier frequencies, the margin between attenuation and gain is made about 10 TU. For frequencies in the carrier range, this margin must be still greater to prevent distortion which becomes objectionable when circulating currents of any size are allowed to exist. This "feed-back" effect will also affect the repeater input impedance, and because of the necessity for closely controlling this characteristic, the margin between gain and attenuation is not permitted to be less than 25 TU at any frequency used for transmission in either direction. The impedance of these filters on the line side must match the line impedance closely in order that no considerable reflection of the carrier currents can take place at this junction point.

As previously mentioned, due to modulation, the output of an amplifier contains other frequencies in addition to those which compose the input, so that cross-talk is to be expected between some of the channels. The amount of cross-talk which appears at the far end depends upon the ratio of the sideband currents to the interfering currents produced in the amplifier, the measurement being made at the repeater output. The near-end cross-talk, however, is dependent upon the level difference between the strong output of the one amplifier and the weak input to the other. Those frequencies which may give trouble in the channels at the near end enter the returning circuit at the amplifier input,—a point where the sideband level is very low. To put the near-end cross-talk on the same basis as the far-end, the output directional filter must introduce enough attenuation in its non-transmitting range to make up this level difference. This attenuation is increased until the near-end cross-talk due to this cause is appreciably less than the far-end.

The output current of one amplifier may be 30 TU or more stronger than the input current to the amplifier for the opposite direction, and the directional filter at the input of this second amplifier must offer sufficient attenuation to the output currents of the first so that they will not contribute materially to its load.

Fig. 40 shows the selectivity characteristics of the two directional filters.

A pair of filters having important functions is the line filter set which, as has been noted, acts to separate the carrier currents from the regular speech currents on the common line circuit. It consists of a high-pass and a low-pass filter paralleled on the line side. Currents entering these terminals from the line circuit pass through the high-pass circuit, to the carrier apparatus, or through the low-pass circuit to the circuit terminal or repeater. The transmission characteristics of these filters are shown on Fig. 41. It will be noted that frequencies above approximately 3300 cycles are transmitted in the high-pass circuit, and frequencies below about 2800 cycles are transmitted through the low-pass circuit. In addition to those which are normally in use for carrier transmission, it is common to equip a few line circuits with line-filter sets. This makes it readily possible in case of an emergency, or for other reasons to use the spare wires thus equipped for carrier transmission.

Non-linear effects may be produced in the coils and condensers in the circuit. The design of the filter parts must be made so that these effects will be a minimum. This requires the use of non-magnetic cores in the coils, and also that the containers be of non-magnetic material. Condensers in magnetic containers must be located so that they will not lie in the field of the coils, and thus contribute to the modulation products. The modulation in the line filters, telegraph composite sets, and office and cable loading units must also be considered.

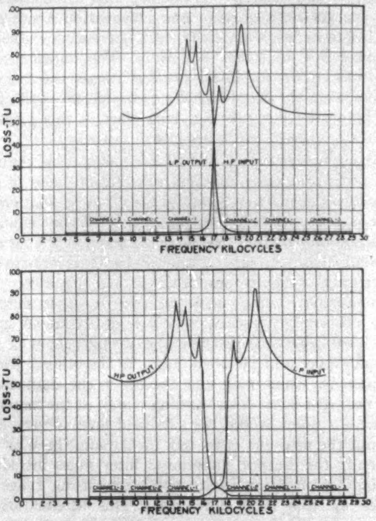

Fig. 40—Typical Directional Filter Characteristics

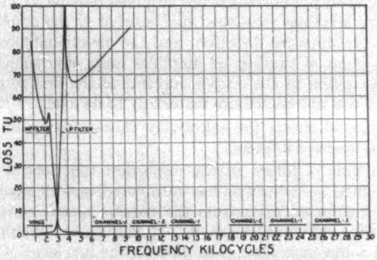

Fig. 41—Typical Line-Filter Characteristics

As already mentioned, care has to be exercised in the mounting of filters belonging to different systems in the same office, so that no cross-talk will be introduced from one system into another. A considerable level difference may exist between two filters of different systems, and it may be desired to mount these filters on adjacent bays. In order that the cross-talk between these two systems may be kept within desirable limits, the separation between the filters must correspond in attenuation loss in some instances to the order of 120 TU, or one part in a million. To meet this exacting requirement, the filters are totally incased in sealed copper boxes, the leads being brought out through small holes to terminal blocks.

*Amplifiers.* As previously mentioned, the amplifiers employed with the type *C* system at the terminals are identical with those used with the repeaters at intermediate stations. Therefore the following is applicable to both cases:

The number and size of tubes needed to deliver the necessary output level or power are largely controlled by interchannel cross-talk requirements. With the grouping frequency arrangement, the three bands which transmit in the same direction are amplified in a common circuit. In passing through the common amplifier, the different sideband frequencies must not react upon each other to produce other frequencies of sufficient magnitude to cause interference. For example, second harmonics of the lowest band frequencies lie within the range of the highest channel in the lower group. If these harmonics are permitted to become too great, troublesome noise will be present in the highest channel when speech currents flow in the lowest. In order that this interference or cross-talk may not become excessive, the tubes used in this amplifier must be made of ample power capacity. This example of interference caused by the second harmonic shows the desirability of using a push-pull amplifier in carrier repeaters because of its property of balancing out second order effects, which in a single-tube or unbalanced circuit are the largest of all the modulation products at the usual loads.

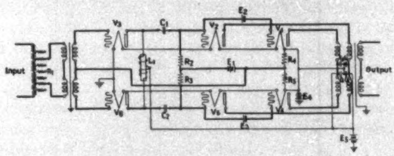

Fig. 42—Amplifier Circuit

The currents from the three channels enter the carrier amplifier shown in Fig. 42. The circuit consists of two stages; the first stage of two tubes, the second of four of higher power rating. The gain is controlled in 2-TU steps by the adjustable potentiometer in the input. The gain frequency characteristics for different potentiometer settings are substantially flat within a small fraction of a TU over the range of any channel.

The amplifiers for the two directions are of slightly different design, each amplifier being arranged for a flat characteristic over its own group of frequencies. It has been stated that the load capacity of the amplifier is limited[10] by the modulation products which increase with the load. Fig. 43 shows the amount of second and third harmonics produced in a typical repeater with varying single-frequency output. By connecting the tube in push-pull instead of in parallel, the second harmonics have been reduced by about 15-20 TU.

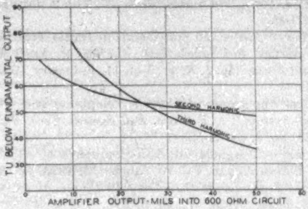

Fig. 43—Amount of Second and Third Harmonics as Function of Carrier Repeater Output

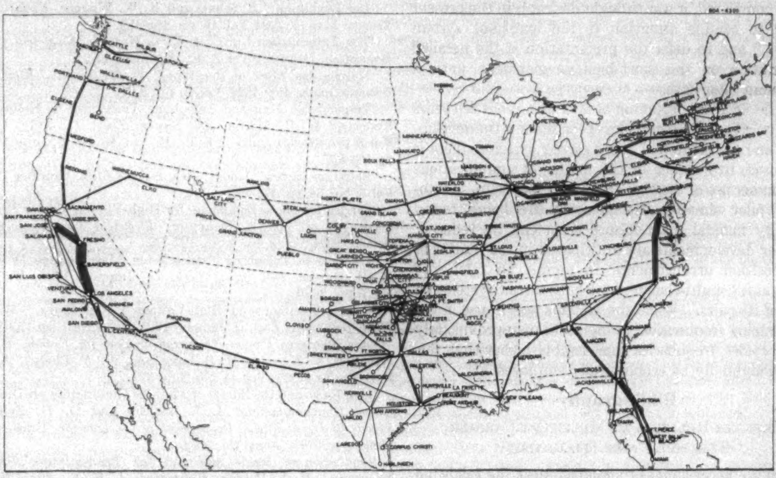
SEATTLE
CLE ELUM
SPOKANE
PORTLAND
WALLA WALLA
THE DALLES
EUGENE
BEND
MEDFORD
REDDING
WINNEMUCCA
ELKO
SALT LAKE CITY
RAWLINS
PRICE
GRAND JUNCTION
DENVER
PUEBLO
STERLING
NORTH PLATTE
OMAHA
GRAND ISLAND
CONCORDIA
SACRAMENTO
SAN FRANCISCO
SAN JOSE
SALINAS
MODESTO
FRESNO
BAKERSFIELD
SAN LUIS OBISPO
LOS ANGELES
SAN PEDRO
AVALON
ANAHEIM
SAN DIEGO
EL CENTRO
YUMA
PHOENIX
TUCSON
EL PASO
PECOS
AMARILLO
BORGER
CLOVIS
LUBBOCK
STAMFORD
SWEETWATER
FT. WORTH
ABILENE
SAN ANGELO
BROWNWOOD
KERRVILLE
SAN ANTONIO
LAREDO
CORPUS CHRISTI
HARLINGEN
HOUSTON
BEAUMONT
PORT ARTHUR
DALLAS
PALESTINE
HUNTSVILLE
WICHITA
GREAT BEND
LARNED
GARDEN CITY
HAYS
COLBY
LIMON
WOODWARD
ENID
OKLAHOMA CITY
LAWTON
WICHITA FALLS
MCALESTER
FT. SMITH
LITTLE ROCK
TEXARKANA
SHREVEPORT
ALEXANDRIA
LA FAYETTE
NEW ORLEANS
JACKSON
MERIDIAN
BIRMINGHAM
ATLANTA
MACON
WAYCROSS
JACKSONVILLE
DAYTONA
ORLANDO
TAMPA
FT. PIERCE
WEST PALM BEACH
MIAMI
SAVANNAH
CHARLOTTE
GREENVILLE
NASHVILLE
KNOXVILLE
MEMPHIS
POPLAR BLUFF
EVANSVILLE
LOUISVILLE
CINCINNATI
LYNCHBURG
ST. LOUIS
ST. CHARLES
SEDALIA
KANSAS CITY
ST. JOSEPH
TOPEKA
JOPLIN
SPRINGFIELD
TERRE HAUTE
BLOOMINGTON
CRESTON
DES MOINES
WATERLOO
DAVENPORT
DUBUQUE
MADISON
CHICAGO
LOGANSPORT
MANSFIELD
PITTSBURGH
HARRISBURG
MINNEAPOLIS
MANKATO
SIOUX FALLS
TOMAH
HIBBING
PETOSKEY
GRAND RAPIDS
JACKSON
DETROIT
BUFFALO
ELMIRA
NEW YORK
BOSTON
CONCORD
PORTLAND
BANGOR
BURLINGTON
NEW HAVEN
BUZZARDS BAY

Fig. 44—Map showing Carrier Telephone Systems Throughout Bell System

Other products of modulation, as well as the second and third harmonics, increase with the output and thus the power which can be taken from the amplifier under the operating conditions is limited, as these effects are likely to result in interchannel interference.

When the alternating voltage applied to one grid is positive with respect to the filament, that on the other grid is negative. Since the even order products are proportional to an even power of the input voltage, these currents will flow through the high-side winding of the output transformer non-inductively producing no flux in the transformer, and hence no current in the low-side windings. To realize this ideal condition, the two currents flowing in the output transformer windings must be equal in amplitude, and 180 deg. out of phase. Since the plate current is a function of a number of tube constants, like amplitudes can be obtained in several ways. Tubes which will give the same harmonic current may therefore be selected; that is, tubes in which the net effect of the several factors is the same.

## Conclusion

*Use in Telephone Plant.* The carrier systems are meeting successfully and economically the requirements of long distance telephone service. From what has already been written, however, it is evident that by its nature, the apparatus is complex and to a fair degree expensive, so that for the relatively short distances, it is cheaper to string additional wire. The exact distance beyond which it is more economical to employ carrier methods is obviously dependent upon the circumstances surrounding each particular case. Systems are operating for distances of 150 mi. and upwards.

Often where there are longer haul continuous physical circuits on the same line traffic growth requires additional circuits for the shorter distances. In such cases, it is not uncommon to break up the long-haul physical circuits into sections to satisfy the short-haul circuit growth and to install a carrier system to meet the long-haul needs.

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[10] F. C. Willis and L. E. Melhuish, "Load Carrying Capacity of Amplifiers," *Bell System Tech. Jl.*, Vol. 5, October, 1926, pp. 573-592.

The growth of the use of carrier systems has already been pictured. How the systems are distributed over the lines of the Bell System is shown on Fig. 44. The heaviest density of use occurs in the middle and western sections and in general where the circuit demand and growth have not reached the large figures required to justify the installation of toll cables. The section west of the Mississippi, in particular, is a promising field for the application of carrier systems.

*Future.* While the type *C* system satisfies those circuit-growth demands for moderate- and long-haul, there has remained undeveloped a considerable field for carrier methods over the shorter distances where hitherto only wire stringing has been economical. Very recent developments have resulted in the trial and early field applications of a simple single-channel carrier telephone system designed particularly to meet these shorter-haul demands and thereby to secure the greatest practicable economy in providing facilities by carrier methods in the Bell System. Naturally it is finding its most extensive use in the sections of the telephone plant where the shorter circuits predominate. Because of the fact that the type *D* system development is only now being completed, it was thought desirable in the present paper to confine attention to the long-haul system (type *C*) and to defer the presentation of the detailed information on the short-haul development until a somewhat later date.

While since the beginning of their use, about ten years ago, considerable progress has been made in the development and application of these carrier systems, there is still much to be done in the matter of simplifications and further use of the high-frequency spectrum. Automatic pilot channel arrangements are being tested whereby manual maintenance costs can be reduced. Further developments are anticipated in the matter of transposition arrangements to permit an open-wire line to carry multi-channel long-haul carrier systems on most of its pairs. While the systems now in use in the field employ frequencies no higher than approximately 30,000 cycles, frequencies considerably higher than this can undoubtedly be economically employed.

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## Discussion

**C. S. Demarest:** Certain points in connection with the development of the equipment referred to in the paper are perhaps of sufficient interest to warrant a few further remarks.

The amount of carrier telephone equipment in the plant of the Bell System is becoming quite large in those sections of the country in which open-wire circuits predominate. Approximately 150 systems are now in service on the longer circuits and the number is growing rapidly. In some installations this equipment, together with the repeaters and other associated apparatus of generally similar character, may comprise a considerable part of the total equipment other than the switchboards.

The satisfactory functioning of this equipment is vital to the service which the carrier system performs, since it is the basic means of providing the speech channels for additional facilities. Certain of the wiring and equipment arrangements affect both the performance of the systems and their practical application. Consequently, the details of these arrangements have required careful consideration.

Some of the problems have had to do with the matter of providing effective electrical separation between apparatus units and between wiring, while at the same time permitting assembly arrangements which would be desirable for plant use. The relatively high frequencies and large power-level differences occurring in the carrier systems, as compared with those encountered at voice frequencies, have necessitated some special provisions in this regard. Level differences as great as 50 TU, amounting to a power ratio of 100,000 to 1, may sometimes occur between apparatus units desired to be located closely together.

With ordinary telephone apparatus it has often been the practise to wire many individual apparatus units to terminals at a central distributing frame, in order that interconnections between units might be readily changed. With that part of the carrier apparatus involving high-frequency currents it has been desirable to modify this practise. The line equipment, for example, has been grouped together in one assembly and none of the individual apparatus units in this group has had wiring brought out to the distributing frame. This has reduced considerably the total length of the wiring per circuit within the central office, with consequent reduction in the losses and impedance variations which may be caused by this wiring. This has been a factor of some importance at carrier frequencies because of the relatively large capacitance per unit length of the office wiring as compared with the outside line wires.

Crosstalk between circuits which might occur in the wiring between apparatus units in this portion of the equipment is effectively prevented by using shielded cable. Special precautions are needed at the points in the high-frequency circuits where the conductors may be exposed electrically, even to a small extent. The connections between the lines wires and the group of apparatus comprising this line equipment are made at the top of the equipment bay by soldered connections to terminals arranged in rows less than ½ in. apart. Ordinarily, in voice-frequency circuits, the conductors in different phantom groups may be connected to adjacent rows of such terminals. In the case of the high-frequency carrier circuits, however, it has been found desirable to use only alternate rows of terminals, the intervening rows being strapped together and connected to ground so as to form a shield between the others. Somewhat similar precautions have been found desirable in the wiring to the jacks in the jack panel for the line equipment.

In order to permit mounting compactly the apparatus in the high-frequency portion of the circuit, it has been necessary to employ shielded units such as coils, etc. This has made it possible to locate such coils for separate circuits both on the front and back of the same panel. In the case of the filters, satisfactory shielding has been obtained only by assembling these in sealed copper cans, the ordinary removable can covers used in other telephone equipment being subject to sufficient leakage field at the junction point between cover and panel to make them unsuitable for filter use. With this type of shielding, the filters have been satisfactorily free both from crosstalk and from variations in characteristics due to the effects of surrounding apparatus of different types.

In caring for such requirements it has not only been necessary that the carrier telephone equipment should function satisfactorily of itself, but it has been essential that it should be capable of being correlated readily and flexibly with the circuits and equipments of various types in the plant. It has been advantageous to employ for the carrier equipment the panel-type mounting and assembly arrangements generally similar to those now used for much of the other toll equipment. This has not only effected the desired uniformity in design, but has provided features particularly adapted to the carrier equipment itself, as in the case of the line equipment just mentioned. It has also afforded the desirable features of economy in floor space and accessibility for maintenance purposes.

**C. W. Green:** One phase of this problem, the development of carrier systems, which I might amplify, is the question of crosstalk. The crosstalk between carrier systems on the same pole line is taken care of quite generally by transpositions. There is another problem, though, the crosstalk between the channels of a system, which requires attention in the development of apparatus for the carrier systems.

The currents of the three channels pass through a common amplifier and the characteristics of an amplifier are such that there are produced in the output, harmonics of the input frequencies, frequencies which are the sum and differences of the input frequencies and other combinations of the input frequencies. The design of the amplifier has to be such that these products of modulation are kept down very considerably in order that the crosstalk between channels will not be troublesome. This requires that, by care in the design and operation of the carrier amplifier, these products of modulation be maintained at lower levels than are usually necessary in voice-frequency amplifiers.

**D. I. Cone:** As shown on Fig. 44, much use has already been made of type C carrier telephone systems on the Pacific Coast and to points east now comprising 31 systems with 26,600 channel-miles of circuits. Extensive additional applications are now being engineered. These systems have made a splendid record in actual performance and providing for the large growth in long-distance telephone service pending the orderly development of the cable network. One of the two leads between San Francisco and Los Angeles is now carrying eight systems (24 channels) on two crossarms for a distance of 250 mi. This unusual density of concentration was secured in this case without sacrifice of the high quality and freedom from inter-system crosstalk.

# Superimposed High-Frequency Currents
## for Circuit-Breaker Control

BY LEON R. LUDWIG[1]
Associate, A. I. E. E.

*Synopsis.—On railway or polyphase power systems having a multiplicity of parallel lines, there are unique possibilities in superimposing on the lines a frequency of the magnitude of 500 cycles, (together with the consequent apparatus), to gain selective protection under all fault conditions. The principle suggested is to measure the impedance of the power system with 500-cycle current and high-frequency relays, so placed that under abnormal conditions the impedance of a faulty line, as measured by the relays protecting that line only, is sufficiently low to cause circuit breaker operation.*

*The advantages of such a protective system would be:*

1. *Perfect selectivity between parallel power lines, such that a faulty line may be isolated without disturbing other lines.*
2. *Instantaneous operation.*
3. *Simultaneous operation of protective breakers at the two ends of a faulty line.*
4. *Protection of the line against short circuits or faults, but the avoidance of breaker operation on heavy overloads when the current rush may be greater than at short circuit.*
5. *A measure of the continuance of a fault, permitting automatic reclosing of circuit-breakers.*

*This super-frequency control system brings to light a number of refreshing conceptions, and while it is not completely developed at this time, sufficient experimental work has been done to warrant presenting the results as a matter of technical interest.*

### THE CIRCUIT-BREAKER CONTROL PROBLEM

ANY relay or other type of apparatus called on to control circuit-breakers automatically, must meet an increasing number of rigorous qualifications. In addition to causing the breaker to operate if excessive currents arise in the system to which it is applied, there is a number of other requirements which are essential, or desirable, all or some of which must be fulfilled, depending on the system.

First, the system to be protected may consist of parallel feeders, any of which is liable to a fault. Should one of the parallel feeders become faulty at any point, it is essential that this feeder be disconnected from the system by opening circuit-breakers at both of its terminals, but parallel feeders should remain undisturbed. This desirability of perfect selectivity between parallel conductors may, if the fault occurs near one terminal, tax the ordinary relay beyond its limit of differentiation.

An increasingly important requisite is the high speed of both relay and circuit-breaker operation. On power systems, the ability of protective apparatus to isolate a fault rapidly is an important asset in maintaining stability. The dynamic stability may be greatly increased if the time required to remove a fault is somewhat less than that required for synchronous machinery to shift its phase angle appreciably. In case of nearby parallel telephone lines, telephone interference may dictate rapid isolation.

On many systems having a widely divergent load demand, heavy-load currents may exceed short-circuit currents if the short circuit occurs with the minimum of generating capacity connected to the line. The control equipment must act to isolate the short circuit, but should not open the loaded line, a condition which precludes the use of plain overload relays.

There are other desirable features of relaying systems, three of which may be mentioned. Circuit breakers are frequently tripped to temporary faults, in which case, if the relay could determine the nature of the fault, the breaker might be again closed and normal conditions restored without the need of an operator. Automatic reclosing would be particularly advantageous if, with the circuit-breaker open, the relay could determine whether or not it might safely be reclosed. From the standpoint of telephone interference, a further requirement is the simultaneous operation of the circuit-breakers which are to open, or the avoidance of "cascade" operation. The third feature is a relay system which could be set and tested for proper operation without the necessity of actually placing a short circuit on the power system.

A combination of the above problems has so strained the usual concepts of relay procedure that an entirely new basis of circuit-breaker control is desirable and may be found in the application of a superimposed high-frequency current system. The purpose of the new system is therefore to extend the limitations naturally imposed by the use of normal frequency relays.

### DESCRIPTION OF THE SYSTEM

The 500-cycle system consists essentially of a source of high-frequency power, a means for introducing it into the lines to be protected, means for obtaining selectivity in case of parallel lines, and the circuit breaker operating relays. The system is equally applicable to a single-phase railway system or a polyphase power system. An application to a single-phase system may be described first for simplicity. In Fig. 1 is shown a grounded single-phase system, which may be a railway network. There are two parallel contact lines supplied with power from transformers located in three substations. A circuit breaker is placed in each end of each contact line.

The 500-cycle current is introduced into the system by a connection from the generator or power source to the ground side of the main transformer. The other

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[1] Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

terminal of the power source, which is usually a small high-frequency synchronous generator, is connected to the ground. A high-frequency power source is necessary at each point in the network where power current of normal frequency is supplied. To prevent the high-frequency generator from being short-circuited by this connection, a resonant device consisting of a condenser in parallel with an inductance is placed in the main power circuit between the point of connection of the generator and ground. The condenser and inductance are each designed to have the same reactance at the high frequency, and therefore if their resistance is low, their combined impedance will be very high. Currents of normal frequency pass easily through the inductance, which has in itself a very small impedance. The parallel circuit may be referred to as a "blocking shunt."

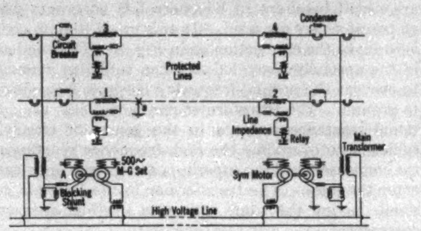

Fig. 1—Protective System Applied to a Single-Phase Network

In order to gain selectivity between parallel lines, a device similar to the blocking shunt, though very much smaller, is placed in each end of each line. Its function is purely as a line-impedance at the high frequency, with the advantage that considerable impedance may be obtained by the use of a very small reactor in this way. A high-frequency current will circulate in the parallel line-impedance which is proportional to the high-frequency current in the line. The relay itself may therefore be connected to a current transformer placed in the condenser branch of the line-impedance. The condenser will carry very little of the power current, which means that the relay will function solely on high-frequency current proportional to that in the line.

### Description of Operation

Normally, with no fault or load on the contact lines, the generated voltages of the high-frequency machines are equal and opposed. These machines will synchronize and there will be no appreciable current flowing in the contact lines. To further aid in keeping the voltages opposed, the generators are driven by normal-frequency synchronous motors, which will maintain an almost constant phase position.

If a ground occurs at (a) on one of the lines, high-frequency current will flow from the generator through the main transformer to the contact line, then to ground through the fault, and return. An appreciable current will therefore circulate in the resonant line impedance (1) and (2), sufficient in magnitude to trip the corresponding relay. Some current will also flow from the generator *B* through the line (3-4), but this current will be less in magnitude because it must pass through three line-impedances instead of one as in the former case. Then the current in the parallel line will not be sufficient to trip the relays at (3) and (4). For similar reasons, the remaining relays in the adjacent lines will not be tripped.

In case some form of load is connected to one of the contact lines—a locomotive for example—high-frequency current will flow to ground through the load, but will not be sufficiently great to trip any of the relays because of the load impedance. It is fundamental that the high-frequency current always provides a means of measuring impedance regardless of the network. Normal speeds of rotating machinery are so much below the high-frequency synchronous speed that practically no counter-voltage is generated at this high frequency. It is also usually the case that the blocked impedance of the load is high in comparison with line impedances, which means that there is a good margin of differentiation between heavy loads and short circuits. In brief, the high-frequency system may be looked upon as a network equivalent to that of the normal frequency except that all normal frequency rotating apparatus may be considered as blocked.

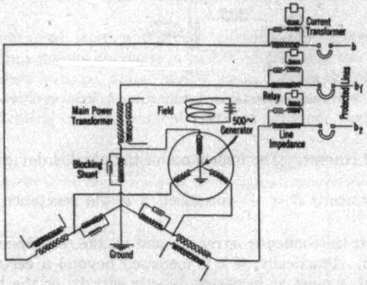

Fig. 2—Protective System Applied to a Three-Phase Network

### Polyphase Application

The means of using this apparatus on a polyphase system is shown in Fig. 2. The high-frequency generators must now be polyphase. Their current may be introduced in the neutral side of the main transformer winding, three of the blocking shunts per power source being required. It is assumed that the main transformers are connected in star with a grounded neutral. Otherwise, the method of connection will be given later. If there are parallel lines, line impedances must be used as before. The principle of operation is the same; namely, that the high frequency is introduced and the line impedances are so placed that the impedance measured by a given relay is the correct impedance to cause that relay to trip, provided there is a fault on the line it protects. By tracing the path of current in the diagram, it can be seen that a short circuit between lines ($b_1 - b$) will cause a relay-actuating current to flow.

### DISCUSSION OF SPECIAL PROBLEMS

The system depends so largely for its successful operation upon the parallel resonant circuits that special mention of their properties will be made. If the condenser and reactance are resonant at the chosen high frequency—500 cycles for example,—then at 25 cycles the reactor will have one-twentieth of its high-frequency reactance. The condensive reactance will be increased twenty times at normal frequency, or 1/400 of the load current will pass through the condenser. The reactor must be designed, therefore, to carry the load current. The impedance of the parallel device is very nearly $Z = \frac{x^2}{r}$ in which $x$ is the reactance of either the condenser or reactor and $r$ is the resistance of both. Practically, if $x$ is increased beyond a certain point, $r$ must be increased directly with it, or the impedance will vary as the first power of the reactance.

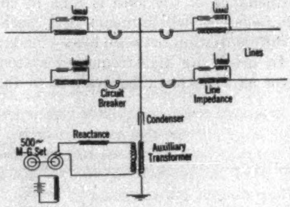

FIG. 3—SPECIAL METHOD OF INTRODUCING AUXILIARY CURRENT INTO A LINE

It is easy to obtain an impedance of a few hundred ohms, which is sufficient for the blocking shunts, with a comparatively small reactor and a single condenser unit. The line impedances require about 40 ohms, which is very easily obtained.

In certain networks the blocking shunts may serve another function than previously explained. It may be desirable to subdivide a complicated system into a number of simple high-frequency systems in order to measure the impedance of the simplified systems. The ability to do this by inserting the blocking shunts at predetermined division points, is very important because the most involved network may be resolved into a number of small networks for the purpose of facilitating high-frequency relay protection.

There is a special problem also in getting the proper connection of the high-frequency power to the protected lines. To avoid insulation to ground of the high-frequency apparatus the connection in Figs. 1 and 2 is made on the low side of the transformer. This method is feasible because the reactance of a large power transformer is low. The transformer reactance is, in fact, helpful because the high-frequency system should be laid out in such a way that short circuits on the protected lines are loads, not short circuits, upon the protective system. In some cases, however, there are circuit breakers to be controlled at points where no transformers are used. In this event, the procedure is to make the connection as in Fig. 3. The condenser in the specially provided tap has sufficient reactance to prevent the normal-frequency currents from flowing to ground. The transformer reactance, plus the additional reactance inserted in the generator circuit, is sufficient to overcome the high-frequency reactance of the condenser, and the superimposed current may easily enter the lines. The transformer in the figure is very small, having the same rating as the high-frequency generator.

In three-phase systems, the transformers may be delta-connected, or there may be no ground. A high-frequency ground may be provided by connecting the neutral to ground by means of a condenser. In case of the delta-connected transformers, the method of introducing the current shown in Fig. 3 may be used in three-phase form.

There are a few special considerations in the use of 500-cycle synchronous machines and the steps taken to keep them in phase opposition. The power required from these machines is that necessary to operate the relays and supply the high-frequency line loss. Two kilowatts are ample for a large system. Machines of this frequency synchronize quite as well as those of lower frequency, provided too much reactance is not present between the two. The length of a section of line to be protected is often sufficiently short so that the reactance between generators will not cause synchronizing difficulty. In case it does, however, the high-frequency voltage may be stepped up by means of a transformer in order to decrease the effective reactance. Normally the high-frequency potential need not be more than 250 volts, though it may run much higher on long lines.

Fig. 1 shows the generators driven by synchronous motors connected to the main power feeder. If this connection is made, there are two closed systems interconnecting the motor-generator sets at two frequencies. If there is a difference in the phase angles of the voltages of power frequency at the two motor-generator sets, there must be flexibility in the inter-connection. This flexibility should occur in the power-frequency side of the motor-generator sets and may be obtained by the use of a flexible coupling between the two machines of the set, or by placing reactance in series with the synchronous driving motors. Either of these devices will aid in keeping the high-frequency voltage closely in phase. A synchronous driving motor has been selected because it permits the auxiliary generators to supply power at constant speed and frequency. The constant frequency is essential to prevent the parallel shunts and line impedance from departing from resonance.

The final component of the system needing special discussion is the relay. In Fig. 4, a 500-cycle mechanical relay is shown which has two elements connected in series. The function of the relay is to trip if a rapidly rising current of sufficient value is passed through it. This limitation of a rapidly rising current is obtained by the use of the second element. The dashpot shown in the figure will slow down the second element whose function is to tighten the spring restraining the tripping element such that if the current rises slowly a very high value will be necessary to trip the main element. The purpose of using such a relay is to prevent synchronizing currents between the generators, which currents must rise slowly on account of the mechanical inertia of the generators, from causing the relay to operate. A second purpose is to "pre-set" the tripping element as the load upon a section of protected line varies or as the generating capacity connected to the section of line varies.

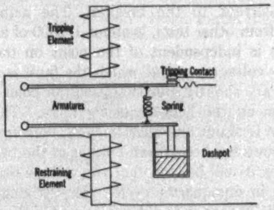

Fig. 4—High-Frequency Pre-Setting Relay-Schematic Diagram

A vacuum tube relay may be substituted very nicely for the mechanical relay, with the advantage of increased speed. A relay used for this purpose is shown in Fig. 5. It is a neon-filled tube with a double purpose; first, to break down at a predetermined voltage in the manner of the well-known glow tube, and second, to pass a high circuit breaker tripping current as a mercury arc rectifier. The two lower electrodes consist of mercury pools, and the upper electrode is a hollow metal cone. If the voltage between the upper electrode and the smaller lower one reaches a given value, a glow discharge occurs between the two, which causes a mercury arc to be formed between the upper and main lower electrodes. The tube is a further development by D. D. Knowles of the earlier Knowles' Grid-Glow Tube. It is capable of momentarily passing a tripping current of a few hundred amperes. The entire action is very rapid.

The connections using the tube relay are shown in Fig. 6. The device at the left takes the place of the pre-setting element on the mechanical relay. The entire relay apparatus in this case operates from voltage, actually the voltage of the current transformer in the line impedance circuit with a high impedance across its secondary. The pre-setting device consists of a one-to-one transformer whose exciting current is obtained from a resonant circuit. The transformer connections are made in such a manner that the secondary voltage, under steady state, opposes the primary voltage and leaves zero voltage across the tube. During the transient, however, as a voltage is applied, the rise of the primary exciting current is very slow, and initially there is a voltage across the tube. Then the tube will operate if the voltage is rapidly increased to the breakdown point, but will not function with a slowly rising voltage.

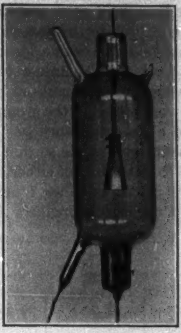

Fig. 5—High-Frequency Vacuum Tube Relay

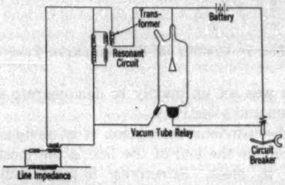

Fig. 6—Circuit Using the Vacuum Tube Relay

Mention has been made of the feature of automatic reclosing of circuit-breakers. If the circuit breakers in Fig. 1 are shunted with a condenser which will pass the high-frequency current only, with the circuit-breaker open, the high-frequency current will retain the relays in their operative position as long as the fault remains on the line. However, at any time that the fault is removed, the relays will return to normal and permit the breaker to reclose. Such a connection would be advantageous if the protected system is liable to faults of short duration.

### RESULTS OF EXPERIMENTAL INVESTIGATION

For the purpose of making an oscillographic study of the system, it was applied experimentally to an 11,000-volt test track contact line at the Westinghouse Works in East Pittsburgh. The experimental circuit is shown in Fig. 7. Four lines were used, and they were joined in pairs at one end in order to give two parallel lines with both terminals at the same location, the latter being for ease in testing. The lines were fed by 11,000-volt single-phase transformer banks at both ends. Two blocking shunts were placed in the grounded side of the transformers and a line-impedance was placed in each line. Arrangements were made so that a short circuit could be applied to either end of either line. Vacuum-tube relays were placed on lines 1 and 4, and were connected to trip the circuit breakers *A* and *B*. The apparatus was set up mainly to demonstrate speed of relay action and selectivity.

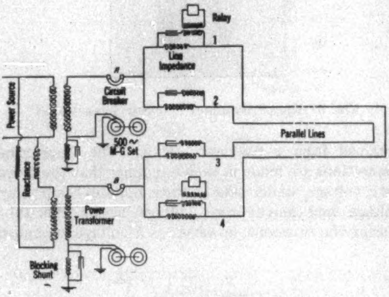

FIG. 7—CIRCUIT OF EXPERIMENTAL TEST

From the previous description it is obvious that a short circuit at the end of the line is the most severe condition to meet. Selectivity is most difficult to obtain, and there is the greatest danger of the auxiliary generators running out of synchronism with the short circuit at this point.

The first tests were made with high-frequency current alone applied to the line. The relays may be properly set, therefore, without the application of power current, by placing short circuits at the various indicated points and adjusting the tube voltage so that it trips with a fault on line (1-4) but not with a fault on line (2-3). The tube relay circuit was that shown in Fig. 6. In making these first tests the low-tension side of the power transformers must be short-circuited.

The frequency used was 525 cycles obtained from a small rotating machine, at 250 volts. Standard oil-filled condensers were used in the impedance circuits; the current transformers also were standard. The oscillogram in Fig. 8 was taken with a short circuit at the end of line 1. The lower element recorded the high-frequency current flowing from line to ground. The other two elements are a record of the current in the upper electrodes of the tube relays at 1 and 4. It will be recalled that both the circuit breaker tripping current (d-c.) and the high-frequency breakdown current flow in this electrode. The film, then, shows the high-frequency current superimposed upon the direct current. The d-c. component is similar to that which flows in the tripping coil of a circuit breaker, and the shape of the curve is familiar. The high-frequency component will be seen to gain in magnitude. The first tube operated two and one-half cycles, high frequency, after the short circuit occurred, and the second tube, two cycles later.

A potential of 11,000 volts was then applied to the lines at a frequency of 25 cycles. A short circuit was placed on line (1-4) at 4, and Fig. 9 is a record of the short-circuit current in line (1-4) at 1 and of the current in the tube relay at the same point. There is no discernible time lag from the instant at which the fault was applied to the instant at which the relay furnished tripping current to the breaker. The actual time, obtained from other tests, is about 1/2000 of a second. This time is independent of the point on the power frequency voltage wave at which the fault is applied, but will vary slightly, depending on the point of fault application on the high-frequency wave. The maximum time is about one-quarter cycle, high frequency. Fig. 10 shows the breakdown voltage of the two tubes, from which it will be seen that the voltage reaches its maximum in one-quarter cycle. The striking feature of the films is that it is not necessary for the relay to wait until the power current becomes excessive before operating. It will be noticed that the speed is much greater with power current on the line, because of the initial charge of the condensers. Fig. 11 shows the short circuit and tube currents with a fault on the line (2-3). Neither tube operated, indicating the perfect selectivity.

### CONCLUSIONS

In principle, super-frequency control has four inherent characteristics which contribute to its value. First, high-frequency currents "know more about reactance" than those of low frequency, which means that the small differences in line reactance which describe the distinction between a fault or normal load may be more easily detected with high frequency. In the second place, by the use of certain high-frequency blocking devices placed in the lines, a network having any degree of complication may be broken up into a number of simple networks at the high-frequency, each of which may be independently measured. This possibility provides a high degree of selectivity between various lines, and independent isolation of faulty conductors without the drawback of time delay.

The third characteristic is that, inherently, high-frequency currents reach their peaks or relay operating values more rapidly than those of normal frequency, thus insuring a high speed of relay operation. Finally, the high-frequency superimposed currents measure the pure impedance of a network, which is not possible with low frequency because of the counter-electromotive force of connected machinery. The advantage of the latter is an independence on the part of the superimposed system of all conditions of loading previous to a fault, an advantage which enhances recognition of fault conditions.

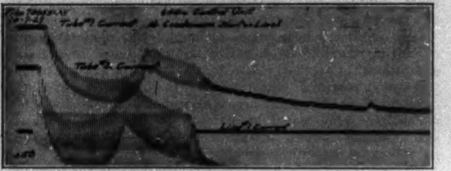

Fig. 8—Oscillogram of Relay Action with High Frequency Alone

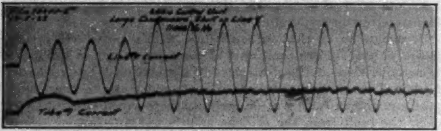

Fig. 9—Oscillogram of Relay Action Under Short Circuit Condition

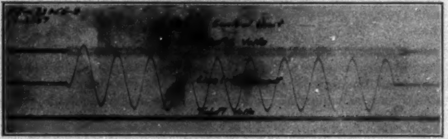

Fig. 10—Oscillogram of Voltage Across Relay During Short Circuit

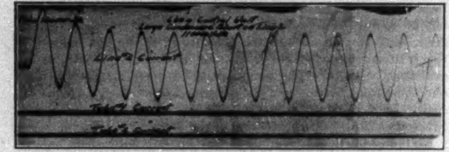

Fig. 11—Oscillogram Showing no Relay Action With Short Circuit on Parallel Line

These inherent advantages lead to many possibilities. In general, the margin by which relays operate or do not operate may be considerably extended. Furthermore, the elimination of many variables in the power circuit by the use of high frequency makes possible accurate and simple calculation of relay operating currents. There are no particularly new principles involved and the system is simple enough to make possible its application to many of the more complex problems in circuit-breaker control.

A great many variations of this super-frequency control are possible, and have entered into experimental work and calculation. The system described has been used in an experimental way only, in order to demonstrate the soundness of its theoretical nature. The results obtained have been interesting and unique, and in themselves predict the future development of a super selective relay equipment.

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## Discussion

**O. C. Traver:** Mr. Ludwig's paper is very gratifying, not only on account of its definite contents but because of the goal sought. In the hope that it may help in the final solution of the problem, some of the handicaps that must be overcome are mentioned below.

Static and steep wave fronts will probably be very unwelcome on lines equipped with this protection. They might be expected to produce the requisite rate of rise to open the breaker on a perfectly good line.

Higher system voltage and frequency also work their hardships, chiefly from the standpoints of costs of the condensers.

The length of the trial line is not given. It is assumed from the general description to be relatively short. As the length increases the difficulties will multiply. Not only will the line reactance become objectionable, but to hold two 500-cycle generators in synchronism over a 100-mi. line, that is one-fourth cycle apart, would seem difficult. The greatest difficulties are apparent.

The use of the rate-of-rise relay suggests that the 500-cycle generators might sometimes fall out of step. Such condition might be fatal to protection should a fault occur during that interval.

The vacuum-tube relay, on its own account, is a very interesting development. It may not be as accurate as mechanical relays, but its speed will commend it, nevertheless.

**R. G. McCurdy:** As Mr. Ludwig indicates in his paper, telephone engineers are interested in any developments which increase the speed of relay and circuit-breaker operation on power transmission circuits, as such developments tend to minimize the interference which may be caused on adjacent telephone lines, during periods of fault or other abnormal operating conditions.

The schemes discussed by Mr. Ludwig, however, while obtaining a desirable result in improving conditions as regards interference under abnormal power conditions, may cause a considerable increase in noise interference on exposed telephone circuits under normal power-circuit conditions. It seems necessary that in order to make any superimposed high-frequency system function satisfactorily, the magnitude of the superimposed currents must be large as compared to the currents normally present on the power circuit in the same frequency range. It is evident, therefore, that the addition of such control currents employing frequencies in the range used for telephone transmission will increase the telephone interference factor of the power circuit and correspondingly increase the difficulties of coordination with adjacent telephone lines. Assuming 500-cycle voltages of the order of two per cent of the normal frequency voltage, as suggested in Mr. Ludwig's paper, this may result in an increase of the telephone interference factor of the power circuit of the order of 3 to 1.

The efforts which have been carried along for the past few years on the part of the power and telephone companies have been effective in reducing both the influence of the power systems and susceptiveness of the telephone systems. It seems very important that any developments for improving the operation of relay systems which would reduce interference under abnormal power conditions shall be worked out in some way which would not involve at the same time an increase in the influence under normal operating conditions. In the application of high-frequency relaying schemes to power circuits it seems important from the standpoint of inductive coordination that either (1) continuous use of the high frequencies be avoided and their application to the system be confined to the sections of line in trouble and for the period while the trouble persists, or (2) that the control currents, if continuous, shall be at such frequencies and power levels as not to interfere with adjacent communication circuits. It would appear that this latter arrangement must in general mean a considerable reduction of the incidental currents of the power circuits near the frequencies involved.

**D. W. Roper:** I should like to inquire if this system can be used for the protection of lines that are entirely underground. I should also like to inquire how the system could be extended, if at all, so as to cover the most awkward case we have in our system in Chicago.

The most awkward system we have for relay protection is on high-potential transmission lines between generating stations—perhaps I should call them tie lines. The stations are of a capacity of upwards of a hundred thousand kw. apiece. There are transformers at both ends, and the lines are all underground cable. The 12-kv. connecting cable may be a few hundred feet up to two thousand feet from the switch to the transformer. The high-potential transmission line 66 kv. may be something of the order of 10 or 20 mi., and then there is at the other end some 12-kv. cable up to, say, 2000 ft. in length.

There are several systems which apparently work fairly successfully for opening the switches if the fault occurs on the high-potential line. The awkward case is where the fault occurs on one of the 12-kv. lines.

I should like to inquire of the author if it appears feasible to extend the application of his system to this particular case.

**Paul MacGahan:** The first impression obtained from the synopsis, and also from a superficial reading of the paper by Mr. Ludwig, is that in this superimposed high-frequency protection scheme there is a means which would be an improvement upon the present relay practise as regards transmission lines and feeders.

I doubt very much whether the author of the paper had this in mind, because the applications described are apparently upon networks of trolley conductors such as for the more complicated railway electrification systems.

It might be confusing to many, and result in unwarranted or at least premature hopes for further improvements in sectionalizing of feeders and transmission lines, to retain such an impression. While such a development might be possible in the future, it seems to me that the complications, such as, for example, in supplying an unfailing source of high-frequency power, synchronized on each bus, would be very hard to overcome and that, therefore, the proper place for this scheme of relay development is for cases that cannot be handled by means of the present highly accurate overcurrent time-element relays, and directional relays, or impedance relays.

Since the invention by the writer of the well known reverse-power relay, consisting of a sensitive watt element, the contacts of which are in series with the contacts of the overcurrent element, together with the duo-directional contact idea, there have been many mechanical and electrical improvements in the relays themselves and a great experience built up in their proper application, so that now there are few cases which could not be satisfactorily taken care of by the modern relays.

**G. B. Dodds:** In working out the details of construction and application of the relay equipment used, considerable attention should be given to the reliability of this equipment so that its addition to the system will not create an additional hazard.

This applies particularly to the construction of the blocking reactors and the manner of connection to the high-tension lines. In the past, considerable grief has been caused by the failure of choke coils connected in high-tension lines and the possibility of a recurrence of this experience should be carefully avoided.

One question which comes to mind is the method of synchronizing the high-frequency generators located in different substations. Can this be done by the use of the existing power-frequency potential transformers? In connection with the question of synchronizing there is a question in our mind whether a dash-pot relay would be suitable to prevent operation on synchronizing current, as it has been our experience that dash-pot relays are not entirely reliable.

The fact that a protective installation of this type can be tested in the field without actually drawing short-circuit current is greatly in its favor. Several power companies consider field testing of relay installations by actually grounding the lines very much worth while, and this testing would be very much facilitated in an installation of this kind.

It occurs to us that in connection with a protective installation of this nature some sort of back-up protection would be necessary, since if the protective equipment on a line failed to function, or a breaker failed to open and stuck in the closed position while a fault was on the line, there would be nothing to clear the fault from the system, as other high-frequency relays would not obtain sufficient current to operate. Of course this same situation exists in any type of balanced protection and is called to mind here only to point out that the current transformers used for the high-frequency relays should if possible be of such type that overload relays could be used in conjunction with them.

As the author states, a great many variations of high-frequency control are possible and it is to be hoped that among these variations one will be found that embodies simplicity and reliability of equipment and operation along with reasonable cost and maintenance. The scheme described by the author has its possibilities and should be developed.

**D. W. Roper:** I should like to ask the author if his scheme of relay protection is applicable to a case which is found in Chicago and other large cities. This case covers high-tension tie lines between generating stations in which the generators are operating at about 13 kv., 3-phase. Transformers located at each generating station change the pressure from the bus voltage to the transmission voltage which may be from 2 to 5 times the generator voltage. The connections between the transformers and the circuit breakers in the generating stations, as well as the entire high-voltage transmission line are underground, lead-covered cables. The protection of the high-voltage transmission cable is not particularly difficult, but this can not be said regarding the lengths of about 1000 ft. of 13-kv. cable at each end of the line forming the connections between the outdoor transformers and the oil circuit breakers. If a failure occurs on one of these cables at one station, for example, the oil circuit breakers at this station will be opened very promptly by the action of the relays; but if the relays at the other station are set low enough to operate under this condition, then they will also operate and open the line in case of through faults when there is no trouble on this transmission line.

**J. R. Coffin:** (communicated after adjournment) The method which Mr. Ludwig has used for obtaining a source of the high-frequency current (see Fig. 1 of his paper) is to provide at each switching station a small synchronous motor-generator set, the motor being driven from the power frequency of the supply line and the generator operating to produce the high-frequency control potential.

The use of these small motor-generator sets involves certain disadvantages which it is believed could be eliminated by the use of another method of producing the control frequency. These disadvantages are as follows:

1. The problem of proper supervision and maintenance for these numerous small synchronous motor-generator sets would be serious, especially if used as indicated in a-c. railway transformer substations, which ordinarily do not have skilled attendance.

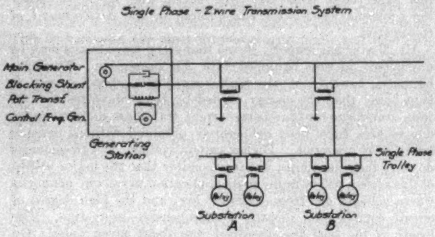


Fig. 1—Application of Central Source of Control Frequency to Single Phase A-c. Railway System

2. The problem of transient interchange of synchronizing power between high-frequency generators at adjacent substations has been covered by Mr. Ludwig in his paper. The presence of these transients requires the introduction of a certain amount of time delay into the relay system which would otherwise be unnecessary.

3. The problem of sustained interchange of synchronizing power between high-frequency generators at adjacent substations is also referred to in Mr. Ludwig's paper. This interchange of power arises because of the phase difference of the power frequency at adjacent substations due to transmission of load along the transmission system, which causes a phase displacement of the motors of the small motor-generator sets. This phase displacement in electrical degrees would be carried over into the high-frequency generators and multiplied by the ratio of the frequencies, so that a relatively small phase displacement in the power frequency would give rise to a much larger displacement in the control frequency. For example, in a railway system operating at 25 cycles a phase displacement of 2 deg. between adjacent substations in the 25-cycle frequency would cause a phase displacement of 40 deg. in the 500-cycle control frequency, which, of course, would result in a relatively large interchange of synchronizing power between the two high-frequency generators. In order to overcome this difficulty Mr. Ludwig has suggested the use of flexible spring couplings in the motor-generator sets. This would permit a reduction of the synchronizing power between adjacent high-frequency generators but it would quite possibly introduce other difficulties due to excessive hunting of the high-frequency generators.

4. Any electrical fault which developed in one of the small motor-generator sets would appear to the relay system as a bus short circuit at the substation and in the absence of special protective devices would result in the isolation of the substation even though no real fault existed on the power system.

The objectionable features just outlined could be avoided and advantages in the way of economy and reduced maintenance could be obtained by substituting a central source of high-frequency potential for the individual motor-generator sets at the substations. Referring to the accompanying Fig. 1, which for the sake of simplicity has been made applicable to a single-phase a-c. railway system, it will be noted that the small motor-generator sets have been eliminated and replaced by a single high-frequency generator located in the main generating plant where presumably it would operate under the most favorable conditions as regards supervision and maintenance. This high-frequency generator introduces into the transmission system a control frequency, the phase position of which at each substation is independent of the load which is being transmitted over the system. This control frequency passes through the ordinary substation transformers and reaches the trolley system without the necessity of any special apparatus at the substation except the small resonant shunts which are used to operate the relays. There is no tendency for a flow of synchronizing power either transient or sustained between the various substations. Should any trouble develop on the control frequency generator in the main generating station, the high-frequency potential would cease, and of course, the system would be left without relay protection until the control frequency was restored. However, the failure of the high-frequency generator would not in itself cause any interruptions or unnecessary circuit-breaker operations. A further advantage accruing from the use of a single high-frequency generator at a central location is the possibility of employing more elaborate apparatus to ensure constant control frequency. As the resonant circuits employed in this system are very sensitive to changes in frequency, difficulty might be experienced due to changes in the power frequency if the two frequencies are mechanically connected through the motor-generator sets.

Fig. 2 herewith, shows the application of the same idea to a d-c. railway system with three different types of a-c.—d-c. substations. The simplest case would be a synchronous-converter substation, as the control frequency would pass directly through the converter and no special apparatus would be required except the relays and resonant shunts. In the case of a rectifier substation there would ordinarily be a reactance choke on the d-c. side of the rectifier which would prevent the passage of the high-frequency control current. In this case the high-frequency control potential could be placed upon the trolley by the use of a potential transformer on the transmission line and a resonant filter circuit applied to the trolley, this resonant filter circuit being designed to pass only the control frequency. An alternate method would be simply to by-pass the reactance choke with a resonant filter circuit, omitting the potential transformer. Resonant shunts for the relays would be required as in the case of the other types of substations. For a motor-generator substation the method of placing the high-frequency control poten-

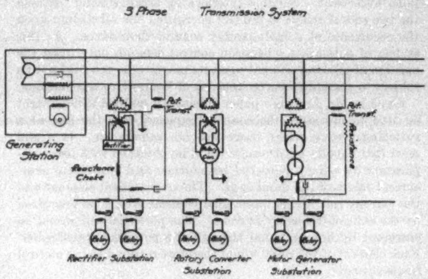


Fig. 2—Application of Central Source of Control Frequency to D-c. Railway System

tial on the trolley system would involve the use of a potential transformer on the transmission system and a blocking shunt in the generator lead. A resistance in the secondary circuit of the potential transformer would also be required. The blocking shunt would then short circuit any frequency which might be present in the transmission system except the control frequency and this control frequency would appear on the trolley system. Resonant shunts in connection with the relays would be required as before.

In Mr. Ludwig's paper it is assumed that the various loads which might be placed upon the transmission system would have relatively low admittance to the control frequency and therefore would not admit a sufficient amount of the control-frequency current to cause difficulty in discriminating between a load and a fault. This assumption seems to be open to question. Assume, for example, that the load is of the order of 10,000 kv-a., and that the source of high-frequency current is of about 10-kv-a. capacity. If the load consists of a transformer and synchronous motor it would have a 25-cycle leakage reactance of perhaps 30 per cent on a 10,000-kv-a. base, which would give a 500-cycle reactance of 600 per cent on a 10,000-kv-a. base, or 0.6 per cent on a 10-kv-a. base, as compared with about 20 per cent in the high-frequency generator itself. The load would of course have no generated counter e. m. f. at 500 cycles. From these figures it seems that the load would appear substantially as a dead short circuit to the control system. This difficulty can be corrected by using a resonant blocking shunt in series with each load.

The use of a blocking shunt on the load suggests the use of a second control frequency for load indicating purposes. For example, in a railway system the locomotive could be equipped with a resonant shunt which would block the relay-control frequency but pass the load-indicating frequency. The load-indicating frequency current could operate a relay which would energize the substation whenever there was a locomotive in the line section on either side and deenergize it when both line sections were clear. Suitable interlocking arrangements between the two sets of relays to prevent energizing the substation upon the occurrence of a fault readily suggest themselves. As this system of automatic substation control depends only upon the position of the load and not upon its magnitude, it would not be subject to complications on account of locomotive regeneration.

Fig. 3 in Mr. Ludwig's paper indicates a method which might be used to introduce the control frequency into the line at a switching station where there was no transformer. It would seem that equally good results could be obtained with less complication by using a potential transformer and directional over-current relays of the usual type. The over-current element and the current coil of the directional element would be energized by the control-frequency current. The potential coil would be energized by line potential through the potential transformer. Each element of the relay would therefore respond to the control frequency only.

**E. A. Hester:** There is one point touched on by Mr. Dodds to which I should like to add a word, and that is the possibility of testing this particular type of protection without actually placing a fault on the system and drawing power current.

In Pittsburgh, we have a network of about the usual complication and we have had a great deal of trouble with grounds. There was a time not so long ago when we tried to predetermine what would happen under various conditions and then set the relay for those conditions. Consequently, many things were overlooked and we had considerable trouble resulting from the operation of the wrong ground relay and often important customers might be shut down.

Finally we decided the only thing to do was to put on actual fault to ground on the line and check the operation of the relays. This is usually done very late at night or at some time of minimum load and by pre-arrangement. Consequently, it is a real hardship on our protection engineer in his organization to get every installation tested. However, within the past two years, we have actually tested most of the installations by putting a ground fault on the line and we have reached a degree of reliability which we once thought we would never be able to reach. I do not mean to say that we have solved the protective problem, but we have found a way to achieve real results with the equipment now available. However, if some means can be found to eliminate the difficulties attending the making of arrangements to make tests at off hours it will be welcomed most heartily and the scheme described by Mr. Ludwig offers real possibilities.

**L. R. Ludwig:** The points brought out in the discussion of this paper have been very well taken, and serve to clarify the problems which were encountered in the development of this system.

Mr. Traver has properly stated that steep wave fronts may be unwelcome on lines equipped with this protection. They are harmless, however, if the high-frequency supplied energy is kept larger than the energy carried by these wave fronts. In tests, transformer-magnetizing-current transients and transients due to arcs, have been deliberately obtained without causing faulty relay operation. Higher system voltages and frequencies do work their hardships, and it is possible that the major utility of this system will be found in its application to railway networks where voltages and frequencies are low, and the high degree of circuit complication dictates comprehensive protection. The length of the trial line described was about seven miles. On such a line it is feasible, and cheaper, to synchronize the generators. For long lines such a procedure would, of course, be impractical, but unnecessary because two or more frequencies may be used with a modified circuit not described in the paper to obviate synchronizing. The rate-of-rise relay has a dual purpose as described, and will prevent relay operation in case the generators are somewhat out of phase, but does not imply that the generators are allowed to fall out of step, which is not the case.

Mr. McCurdy questions the effect on telephone lines of the normal high-frequency currents. Assuming as he does a 500-cycle voltage of two per cent, the telephone interference factor is 30. He has apparently compared this with a factor of 10, which is the best obtainable with pure sine waves. In practise, because of transformer magnetizing currents, etc., systems operate with factors of 20 to 40 regularly. Furthermore, a two per cent voltage is high because the drop in the impedance shunts has been neglected. Also, the telephone interference factor does not tell the entire story, since obviously the ampere-miles of inductive effect cancel out with currents flowing into a section from both ends, and the through-feed currents are necessarily very small because of the impedance shunts. From these facts it is logical to reason that the problem of telephone interference is neither serious nor insurmountable. The problem is further simplified by the fact that the currents are hardly continuous because there are times of light load when practically no high-frequency current will flow. The frequency of 500 cycles, while low on the curve of telephone interference, may not be the best for ultimate use.

Mr. Dodds has raised a necessary question in regard to applying high-frequency apparatus to the lines in such a way that additional hazards are not created. Much depends upon the system to be protected; if it is possible to use small line reactors, they may be connected directly in the line, whereas larger ones would require mounting in a tank of oil equipped with suitable bushings. With regard to synchronizing the generators, this is most easily done by throwing them together regardless of phase position, and letting them pull into step. The dashpot relay has not been used in the form described in the paper, which was diagrammatic, but the relay may gain its time element by electrical means; that is, a mechanical relay may be used in conjunction with the pre-setting transformer shown in Fig. 6. Straight overload relays for back-up protection should be used as pointed out by Mr. Dodds.

Mr. Roper has presented an interesting problem and inquired if a solution is possible by the use of high frequency. So far no tests have been made with cables, and because of their special properties, some difficulties may be encountered. For example, the high-frequency charging current and the effect of the cable capacity will influence the control currents, though there are means of taking these influences into account. So far as the circuit shown is concerned, adequate protection could be secured by properly introducing and blocking the high frequency, but the question regarding cables is at the present time an unanswered one.

Mr. Coffin is correct in stating that there are certain disadvantages in the use of a number of high-frequency generators. This is, however, the most flexible arrangement, and was illustrated because it is applicable to almost any system. In some of the less complicated circuits, numerous simplifications of the system are possible, one of which is shown by Mr. Coffin in his Fig. 1. There is a difficulty in the application shown in this figure, however, which prevents it from being general. Under fault conditions the control current must flow through the high line and transformer, which have considerable impedance. If this impedance is high compared to that of the connected load, it will be impossible to discriminate between load and fault conditions. Blocking shunts in the load circuits could be used as mentioned by Mr. Coffin, but their use was abandoned because of the large expense which they entail due to their being numerous. This point is further clarified by Mr. Coffin's discussion regarding the admittance of loads. The reactance of the load is, in principle, correctly compared to the reactance of the high-frequency generator itself, but reactance in the circuit supplying control current to the lines is disadvantageous in the same way as the leakage reactance of the generator.

In the case of the synchronous-machine load calculated by Mr. Coffin, the figures do not seem complete because the high-frequency and normal-frequency reactances are compared in per cent without taking into account the fact that the voltages at the two frequencies are different. Suppose, for example, that the synchronous motor is supplied from an 11,000-volt line, to which a 250-volt high-frequency generator of 10 kv-a. is connected. The 0.6 per cent reactance of the load as calculated by Mr. Coffin must be multiplied by the ratio of the voltages squared, or the reactance is over 1100 per cent, 53 times that of the generator itself. Calculation using actual ohms impedance yields the same result. In general, the assumption that the load impedance is higher than the line impedance is correct.

The use of high frequency for load-indicating purposes is feasible, and in fact, was one of the first suggested applications of the system described.

The use of a potential transformer for introducing high-frequency currents into protected lines has the objection that the small transformer has too much reactance to permit differentiation between load and fault conditions. A condenser would need to be used with the transformer to neutralize its reactance. Directional relays as suggested, as well as interlocked high- and low-frequency relays, have been used but do not generally seem necessary.

# Extinction of an A-C. Arc

BY J. SLEPIAN[1]

Fellow, A. I. E. E.

***Synopsis.****—The transition from high conductivity to high resistivity which an a-c. arc undergoes on extinction is studied. Theory and approximate calculations are given for the rate of recovery of dielectric strength of the arc space for short arcs, and results are given of experiments on short arcs, and arcs in holes and slots in insulating material and insulating plates. The influence of chemical activity in arc gases is discussed. Factors contributing to the success of the a-c. oil circuit breaker are suggested.*

## 1. INTRODUCTION

THE extinction of an a-c. arc as it is effected in switches and circuit breakers operating in a-c. circuits is fundamentally very different from the extinction of the arc in a d-c. switch. In the latter, by lengthening or otherwise, the arc is brought into such a form that it requires for its maintenance a voltage higher than is generated in the d-c. circuit. The current then decreases, and if the voltage required by the arc remains higher than the generated voltage, the current reduces to zero and the arc is extinguished. In the d-c. switch, then, it is important that the arc voltage be made and kept sufficiently high.

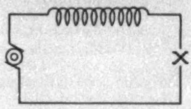
In the a-c. switch, however, the arc while it is playing takes a voltage which is generally smaller than the voltage generated in the circuit, and influences the course of the current only in a minor way. The current following its natural cycle comes to a zero value, and at such a moment, the arc extinguishes. In a very short interval of time embracing this moment of zero current, the medium containing the arc returns from its momentary condition of a comparatively good conductor, carrying current at a low voltage, to its normal condition of a comparatively good insulator supporting the full generated voltage of the circuit with passage of little current. It is this rapid transition at the moment of zero current, from the state of a highly conducting arc to the state of an insulating non-ionized gas which is important for the extinction of the arc in an a-c. switch. This transition must be made sufficiently rapidly if the arc is not to reestablish.

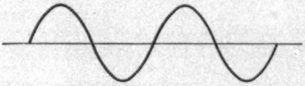
The study of this transition from arc to insulating gas at zero current is therefore not only interesting in itself but is important in that it may reveal principles leading to improvements in a-c. circuit breakers. This paper covers ideas on this subject developed by the author and his co-workers during the past few years.

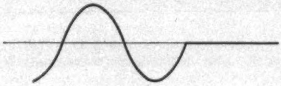
## 2. TRANSITION TIME AND EXTERNAL CIRCUIT

We shall first consider the question of the time available for the transition from arc to dielectric at the current cycle end in a circuit breaker operating in a practical reactive circuit. It is quite clear that this transition requires a finite time to be effected, that it cannot take place instantly. The conductivity of the medium carrying the arc cannot disappear suddenly. Being due, as we shall assume in this paper, to the presence of ions, time must be given for these ions to disappear, either by neutralizing their charges among themselves by recombination, or by discharging into the electrodes. Now how much time is available for this deionization in a practical circuit?

Consider first the circuit of Fig. 1, consisting of an a-c. generator of large capacity, in series with a reactor and an arc. Assuming that the arc voltage is small compared to the generator voltage, the current will lag by nearly 90 deg., as in Fig. 1C. The voltage across the arc will of course be in phase with the current, as in Fig. 1D. Now if at the end of a half cycle of current, the arc should extinguish and the current remain zero, the voltage across the electrodes would at once rise to the terminal voltage of the generator at that time, and because of the phase relationships this would be the peak of the generated voltage. Hence, in such a circuit, no


(a) Circuit with Ideal Reactor


(b) Generated Volts


(c) Current

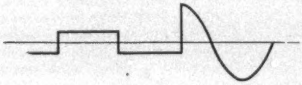

(d) Arc Voltage

FIG. 1

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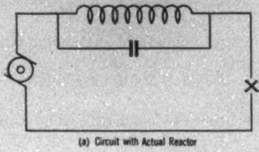
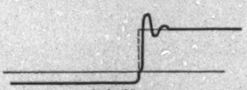
*Presented at the Summer Convention of the A. I. E. E., at Denver, Colo., June 25-29, 1928.*

time whatever would be allowed for the arc to lose its conductivity at the end of a current cycle. If the arc extinguished then, the space would immediately have to support the full generated voltage. An arc whose voltage is low relative to the generated voltage could not extinguish in such a circuit.

However, it is only an ideal reactor which could act to produce the results just mentioned. Every actual apparatus must have electrostatic capacity as well as inductance. An actual reactor may be considered as acting as if it were an ideal reactor shunted by a small condenser, as in Fig. 2A. With such a shunted reactor, the voltage across the arc space will not rise instantly after arc extinction to the generator value, but will come on gradually as the reactor undergoes an oscillation. This is shown in Fig. 2B, on a time scale much expanded as compared with Fig. 1. The time for the voltage impressed across the arc terminals to reach generated voltage is one-quarter of the period of a natural oscillation of the reactor. This we may call the time available for the transition from the conducting arc to the insulating gas space.



(a) Circuit with Actual Reactor



(b) Arc Voltage

Fig. 2

This result can evidently be generalized, and we may say that the time available for transition is always as great or greater than a quarter of a period of free oscillation of the circuit external to the arc. In practical power circuits, the frequency of free oscillation may vary from the order of 100,000 cycles per sec. for the case of a current limiting reactor to only a few hundred cycles for the case of a very long transmission line. The time available for the extinction process in the arc, varies then from 2.5 microseconds to several thousand microseconds depending on the character of the external circuit.

It would seem from this that the interrupting capacity of an a-c. switch may under certain conditions be greatly affected by the nature of the circuit in which it operates.

In experimenting on the extinction of a-c. arcs it proved desirable to control the time available for the extinction of the arc. This was readily accomplished by shunting the arc with an adjustable resistance as shown in Fig. 3. In this circuit, immediately after arc extinction the voltage $V$, rises to the generator voltage value following the exponential curve,

$$V = V_0\,(1 - e^{-\frac{R\,t}{L}}) \tag{1}$$

We may take $\frac{L}{R}$, the relaxation time, as the time available for the transition.

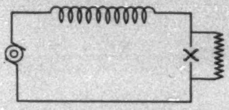
The initial rate of rise of voltage impressed upon the arc space as given by equation (1) is

$$\frac{d\,V}{d\,t} = \frac{V_0\,R}{L} \tag{2}$$

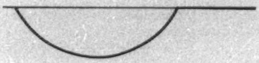
The symmetrical short circuit current of the circuit is $I_0 = \frac{V_0}{L\ \omega}$, and the current which flows through the resistor after the arc is extinguished is $I_R = \frac{V_0}{R}$. Hence the initial rate of rise of the impressed voltage is also given by

$$\frac{d\,V}{d\,t} = V_0\,\omega\,\frac{I_0}{I_R} \tag{3}$$

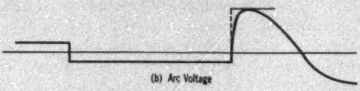
This initial rate of rise of voltage may also be taken as a measure of the time available for the transition, since the arc space must recover dielectric strength at a rate sufficient to withstand impressed voltage growing at the rate given by equation (2) or (3).



(a) Circuit with Shunted Arc



(b) Arc Current



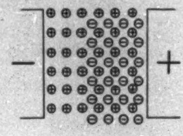
(b) Arc Voltage

Fig. 3

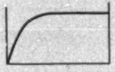
## 3. The Electric Gradient in an Ionized Gas Between Closely Spaced Electrodes

In the last moments of the arc current, and immediately following the current zero, the factors producing new ions have in general ceased their activity, and the ions already in the gas are rapidly diminishing in number by recombination. The rising voltage impressed upon the arc terminals by the external circuit acts therefore upon a gas space containing a diminishing density of ionization. The question then naturally arises as to what is the dielectric strength of an ionized gas as a function of its density of ionization.

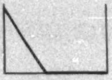
Important in the determination of the dielectric strength is the distribution of the electric gradient in the ionized gas. It is at once clear that the distribution will not be a uniform one. Although, initially, the densities of the positive ions and negative ions may have been everywhere equal, as a result of the application of the electric field this equality is disturbed, and space charges appear which cause the electric field to be distorted. At the cathode negative ions are repelled, and positive ions are attracted. A positive space charge therefore develops in front of the cathode which increases the electric gradient there. Similarly at the anode, a negative space charge and increased gradient also develops.



(a) Distribution of ions in Gas



(b) Potential Distribution in Gas



(c) Gradient Distribution in Gas

Fig. 4

The exact calculation of this gradient distribution is very difficult, although much has been done on this problem by J. J. Thomson, J. S. Townsend, G. Mie, and others.[2] However, we may arrive at a sufficiently good approximation to the gradient distribution for our purposes in the following way. The mobility of the positive ions in the electric field is very small compared to the mobility of the negative ions, which are electrons in the cases in which we are interested. We shall therefore neglect entirely the motion of the positive ions and consider them fixed in space. The negative ions, however, we shall suppose move freely under the influence of the electric field.

With these hypotheses, the effect of the electric field is to move electrons away from the cathode as in Fig. 4, exposing a space charge of positive ions in front of the cathode with charge density, $n\,e$, where $n$ is the number of positive ions per cm.$^3$, and $e$ is the charge of an ion. This space charge causes a considerable portion of the impressed voltage to be consumed in the region next to the cathode. The thickness of the space charge will grow until all the impressed voltage is consumed in the cathode space. Assuming now that the diameter of the section of the ionized gas is large compared to the distance between the electrodes, we may apply Poisson's equation for one dimension and taking $e = 4.77 \times 10^{-10}$ e. s. u. we readily arrive at the following relations.

Thickness of space charge, $d$,

$$d = 1.05 \times 10^3 \sqrt{V/n} \tag{4}$$

Gradient in space charge at distance $x$ from cathode,

$$\frac{d\,V}{d\,x} = 1.8 \times 10^{-6}\, n\,(d - x) \tag{5}$$

Maximum gradient in space charge

$$\left(\frac{d\,V}{d\,x}\right)_{max} = 1.89 \times 10^{-3} \sqrt{V\,n} \tag{6}$$

Mean gradient in space charge

$$\left(\frac{d\,V}{d\,x}\right)_{mean} = 0.95 \times 10^{-3} \sqrt{V\,n} \tag{7}$$

These equations will apply of course only if the thickness of the cathode space charge as given by equation (4) is less than the distance between the electrodes.

## 4. First Approximation to the Dielectric Strength of an Ionized Gas Between Closely Spaced Electrodes

As a first approximation we may assume that electrical breakdown of the ionized gas will occur if the maximum electric gradient in it exceeds a certain critical value. For the sake of definiteness let us take for this critical value, a value approximately appropriate for air at normal pressure and temperature, namely 30,000 volts per cm. From equation (6) then it follows that breakdown will occur when

$$\left(\frac{\partial V}{\partial x}\right)_{max} = 1.89 \times 10^{-3} \sqrt{V\,n} = 30{,}000 \tag{8}$$

or

$$V = 2.52 \times 10^{14} \times \frac{1}{n} \tag{9}$$

The breakdown voltage then varies inversely as the density of ionization, and is independent of the distance between the electrodes, so long as the electrode separation is greater than $d$, given by equation (4).

If the gas is at temperature $T$, we may assume, still as a first approximation, that the critical gradient varies inversely as the absolute temperature. Equation (9) then becomes

$$V = 2.52 \times 10^{14} \times \left(\frac{273}{T + 273}\right)^2 \times \frac{1}{n} \tag{10}$$

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[2] *Handbuch d. Physik*, by Geiger and Scheel (published by Springer), Bd. XIV, page 6.

## 5. THE DECAY OF IONIZATION IN A GAS

During the transition period immediately after the current zero, the dielectric strength of the arc space is rapidly increasing due to the decrease in the density of ionization, as given by equations (**9**) and (**10**). For an arc in the open, the ionization disappears principally by recombination. The rate of loss of ions by recombination is given by

$$-\frac{d\,n}{d\,t} = \alpha\, n^2 \tag{11}$$

where $\alpha$ is the coefficient of recombination.* The solution of this equation is

$$\frac{1}{n} - \frac{1}{n_0} = \alpha\, t \tag{12}$$

where $n_0$ is the density of ions at time $t = 0$. Where $n_0$ is very large, as in the case of the arc which we are considering, $\frac{1}{n_0}$ is negligible, and (**12**) becomes

$$n = \frac{1}{\alpha\, t} \tag{13}$$

The numerical value to take for $\alpha$ in this equation is rather uncertain. For air at normal pressure and temperature several investigators have found $\alpha = 1.3 \times 10^{-6}$ for "aged" ions. Plimpton[3] found values for $\alpha$ for ions aged 0.05 sec. and longer, and an extrapolation of his values for age zero would give $\alpha$ equal to about $7.6 \times 10^{-6}$. As for the influence of temperature at constant pressure, Phillips[4] has found the following variation in relative values at different temperatures.

| Absolute Temperature | 289 | 373 | 428 | 449 | 546 |
|---|---|---|---|---|---|
| $\alpha$ | 1.0 | 0.5 | 0.399 | 0.360 | 0.178 |

For our purposes, probably the best we can do is to take $\alpha$ inversely proportional to the cube of the absolute temperature.

## 6. THE RECOVERY OF DIELECTRIC STRENGTH IN THE TRANSITION FROM AN ARC. FIRST APPROXIMATION, SHORT ARC

Combining the results of sections 5 and 6, we get from equations (**9**) and (**13**) taking $\alpha = 7.6 \times 10^{-6}$

$$V = 1.9 \times 10^9\, t \tag{14}$$

If we take into account the influence of temperature assuming $\alpha$ varies as the inverse cube of the temperature, and that the breakdown gradient varies inversely as the temperature we get

$$V = 1.9 \times 10^9 \times \left(\frac{273}{T + 273}\right)^5 \times t \tag{15}$$

Even allowing for the uncertainty of the numerical constants, these equations show that the recovery in dielectric strength is very rapid. In ten microseconds, if the gas is cold, the arc space is capable of withstanding several thousand volts. According to these equations a low voltage a-c. arc should extinguish in a circuit such that during the transition time the rate of increase of voltage applied to the electrodes is less than between $10^6$ and $10^8$ volts per sec.

Aside from the uncertainty of the constants used in the preceding development, the nature of the departures from the physical facts made in deriving this approximate theory should be borne in mind. First, it was assumed that the positive ions have zero mobility, and that the positive ion density in the cathode space charge is the same as that in the body of the gas. Actually, these assumptions are not true, and an attempt is made in the Appendix to take the mobility of the positive ions into account.

Second, it was assumed that there exists a critical breakdown electrical gradient for air, such that if this gradient is exceeded at any point, the gas will break down. Actually, however, although for larger electrode spacings for a given pressure, the mean gradient at breakdown is nearly constant, for short spacings the gradient at breakdown increases very rapidly as the spacing is decreased. In fact, as is well known, there is a minimum voltage which will produce breakdown regardless of electrode spacing, and for air this minimum voltage is about 300 volts. Account of this factor will be taken in a later section.

Third, it was assumed that the linear dimensions of the section of the ionized gas was large compared to the thickness of the cathode space charge. This will fail to be the case when very small alternating currents are considered or when the arc is confined to small holes or narrow slots, as will be shown in section 12.

## 7. EXPERIMENTS ON THE EXTINCTION OF A SHORT A-C. ARC IN THE OPEN

Some time ago Mr. L. R. Golladay and the author made a study of the interrupting capacity of the multigap lightning arrester. This arrester consists of knurled brass cylinders spaced one-sixteenth of an inch apart, and some of the gaps so formed are shunted by resistors.

Tests on individual gaps were made in a circuit like that of Fig. 3. The arc was started by a small fuse wire, and the shunting resistor $R$ was varied. For sufficiently low values of $R$ the arc would extinguish at the end of the half cycle, but for large values of $R$, the arc would persist. The limiting value of $R$ which would cause the arc to extinguish was determined for currents varying from 100 to 500 amperes, and voltages varying from 300 to 600 r. m. s. Tests were made both at 25 cycles and 60 cycles.

It was found that the limiting resistance varied inversely as the arc current, inversely as the frequency, and was approximately independent of the voltage.

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*Townsend, *Electricity in Gases*, Oxford 1913, Chapter VI.

[3] Plimpton, *Phil. Mag.* (6) V. 25, 1913, p. 65.

[4] Phillips, *Proc. Roy. Soc.*, London (A) V. 83, 1910, p. 246.

These results applied to equation (**3**) show that $V_0 \omega \frac{I_0}{I_r}$ was constant or that $\frac{d V}{d t}$ was constant. Thus the arc would extinguish if during transition the rate of increase of applied voltage was less than a critical value, and would persist if the rate of increase of applied voltage was greater than this value. This critical value was found to be $25 \times 10^6$ volts per sec.

It is interesting to compare this result with equation (**15**). A reasonable value to take for the temperature in the neighborhood of the cathode would seem to be the boiling point of brass or about 1200 deg. cent. Substituting in (**15**) we get $\frac{d V}{d t} = 0.4 \times 10^6$. If we take the melting point, or 940 deg. cent. we get $\frac{d V}{d t} = 1.1 \times 10^6$. These values are rather small compared to $25 \times 10^6$ but agree better with the results obtained in section 11, so that in these experiments perhaps a large part of the discrepancy is due to differences between the properties of zinc vapor and air, as the arc extinction probably took place in zinc vapor.

## 8. Chemical After-Effects in Gases from an Arc

The rapidity of recovery of dielectric strength of the arc space predicted by the preceding theory and confirmed by the experiments described in section 7, would seem to be contradictory with experience, as it is well known that gases coming from switch arcs frequently cause flashover of live parts, hundredths or tenths of a second after the gases have left the arc. However, it appears that it is a chemical activity in these gases because of their composition, which is responsible for their continuing low dielectric strength rather than the fact that they originated in an arc. Thus, in the copper arc, large volumes of copper vapor may be given off at the electrodes. This vapor will burn in air forming a flame. Since the burning as a flame involves the diffusion of oxygen of the air into the copper vapor, and since this is a relatively slow process, the burning of the flame may continue for a considerable time. Such balls of flame are frequently seen rising in the air after the extinction of the arc, when high speed pictures are taken of a copper arc, as for example in a commutator flashover. These flames have a low dielectric strength as long as they are burning. When arcs exist under conditions where little vapor or combustible gas is given off practically no persisting flame is observed after the arc is extinguished.

The substantiation of the above statements lies in studies made by J. E. McGee and L. Dennault, not as yet published.

## 9. Arcs Through Holes in Metal Plates

From the theory so far given, and accepting the experimental value of $25.10^6$ volts per sec. as the rate of recovery of dielectric strength of the arc space, it would seem that an arc in the open air is not a practical means for interrupting a-c. circuits of voltages higher than a few hundred volts. For example in a 2300-volt r. m. s. circuit, the arc space would require $1.3 \times 10^{-4}$ sec. to recover sufficient dielectric strength to withstand the peak voltage of 3250. Practical circuits in general will be faster than this, so that the arc will not extinguish. It is possible, of course, to slow down the rate of rise of the voltage applied to the arc terminals during the transition period by shunt resistors, and equation (**3**) shows that for 60-cycle current the resistors after the arc is interrupted need to carry only five per cent of the current interrupted. Nevertheless, even with this low ratio of resistor current to current interrupted, the resistors become very large and expensive for a high power switch, and for higher voltages the resistor current ratio rises proportionally so that matters become much worse.

It occurred to the author that conditions might be considerably improved if the arc was caused to play through small holes or openings in metal plates. In this way ions could disappear by discharging into the metal plates during the transition time, instead of having to depend only on the recombination in the gas space, and so the deionization would be greatly accelerated. Space charges would be produced in the neighborhood of each plate which would consume some of the impressed voltage so that each perforated plate would to a certain extent, act like a cathode as described in section 3. By having a number of these perforated plates in series, the rate of recovery of dielectric strength would be multiplied proportionally. It was believed, and subsequently substantiated that the arc could play through the perforations of the plates for several half cycles (60-cycle current) without melting the metal, whereas it was believed that the arc terminals were necessarily molten.

Many tests of these ideas were made by J. H. Neher and others. In one, as an example, nine sheets of 16-in. brass gauze, made of 0.032 in. diameter wire, were stacked parallel to each other between two solid copper plates, the sheets being separated by 1/16 in. insulating spacers. An arc of several hundred amperes drawn in a reactor circuit of 2200 volts 60 cycles was then blown into the structure by an air blast, the arc terminals being on the solid end plates and the arc stream playing through the holes in the gauze. Resistance in shunt was varied to determine the limiting value which would cause the arc to extinguish at the end of its first half cycle in the structure. In this way, it was found that the rate of recovery of dielectric strength in the structure was $80 \times 10^6$ volts per sec. or more than three times as fast as for an arc in the open. By using appropriate shunting resistors, current up to 1600 amperes at 6600 volts was interrupted by the structure.

Tests were also made on the rate of deionization occurring when the arc was confined to circular holes of various diameters in plates of various thicknesses. Nine plates, each with a hole and two end plates, were stacked together with insulating separators 1/16 in. thick. The end plates were provided with very fine holes just large enough to pass a fine copper fuse wire. All the holes were lined up, and the copper fuse wire threaded through, and an arc started by short circuiting a small 2200-volt, 60-cycle generator, giving 200-amperes short circuit current, upon the fuse wire. Oscillograms were taken, and resistance in shunt to the fuse was varied so that it would just cause the arc to extinguish at the end of the first half cycle of current. From the oscillograms the rate of change of current, $\frac{dI}{dt}$ at the end of each half cycle was measured, and the initial rate of rise of applied voltage at transition was taken to be $R \frac{dI}{dt}$ where $R$ was the value of the shunting resistance.

The results are given in the curves of Fig. 5. The right hand boundary of each shaded region gives the largest rate of rise of applied voltage observed at which the arc did not restrike, and the left hand boundary gives the smallest rate of rise of applied voltage observed at which the arc did restrike.

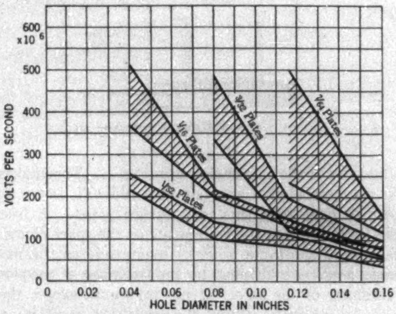

Fig. 5—Arc in Holes in Metal Plates

As was to be expected, the smaller the diameter of the hole, the greater was the rate of recovery of dielectric strength, and for the small holes, values greater than 350 × $10^6$ volts per sec. were obtained. This is 35 × $10^6$ per sec. per plate, and seems to contradict the results of Golladay and Slepian mentioned in section 8, where 25 × $10^6$ volts per sec. was found as the limiting value for a solid cathode. It was hardly to be expected that the perforated plates would act as well as solid plates.

The explanation is to be found in the low voltage per plate, less than 220 volts r. m. s. used in these tests as will be explained in the next section.

## 10. Recovery of Dielectric Strength of Short Arcs at Low Voltages

Equations (**14**) and (**15**) developed for an arc in the open, with solid cathode show that the arc space recovers dielectric strength at a constant rate immediately after extinction of the arc. Experiments at 300 to 600 volts r. m. s. with brass electrodes described in section 7, indicated that this rate of recovery was about 25 × $10^6$ volts per sec. In deriving the equations (**14**) and (**15**) it was assumed that there was a definite critical electric gradient which if it was exceeded at any point, would cause breakdown and restriking of the arc. However, it is well known that the mean gradient at breakdown of short spark-gaps increases rapidly as the length of the gap decreases, and that even for very short gaps, breakdown does not occur with less than a certain minimum value of voltage. For air, this minimum breakdown voltage is about 300 volts, or about 215 volts r. m. s.

It might be expected then, that as the arc circuit voltage is reduced down towards the value 215 volts, r. m. s., the mean rate of recovery of dielectric strength will increase very rapidly, and that for voltages below 215 volts r. m. s., it will be of a different order of magnitude than for voltages much above 215 volts r. m. s.

The same conclusion may also be reached by way of the current ideas concerning the difference in mechanism of a glow discharge and an arc discharge. In the glow discharge, it is believed that all the ionization is due to collisions of ions caused to move with sufficient velocity by high electric gradients. In the arc, it is believed that other factors produce ionization, such as high temperatures, or direct action of $10^6$ volt/cm. gradients upon the cathode, etc.[5] At the time the current passes through zero these other factors have ceased their activity. If the discharge is to restrike, it must restart as a glow. But the glow discharge requires for its maintenance a certain minimum voltage, the normal cathode drop, and this normal cathode drop is very nearly equal to the minimum sparking potential of the gas.

Thus, we again conclude that the first few hundred volts of dielectric strength are recovered almost instantly as compared with the recovery of the later increments of dielectric strength.

## 11. Experiments on Recovery of Dielectric Strength of Short Arcs at Low Voltages

The conclusions of the preceding section found confirmation in the following experiment. Sheets of copper were stacked together with 1/16 in. separators, and an arc of several thousand amperes in a circuit of adjustable voltage from 2300 volts down, was blown into the structure, thus causing a series of short arcs to be produced between successive sheets. A suitably disposed magnetic field then caused these arcs to move in an annular path, and the arcs retraced this path so rapidly that practically no melting or burning of the metal sheets resulted. Details as to the construction of these sheets and the magnetic field will be given in a later paper. As a result of the lack of melting of the sheets there was no flame of burning copper vapor to complicate the results as described in section 8, and it is probably correct to say that the arc extinction took place in air rather than in copper vapor.

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[5] K. T. Compton, Trans. A. I. E. E., Vol. XLVI, 1927, p. 868.

The number of copper sheets was varied, also the circuit voltage and the value of shunt resistance which would just cause the arcs to extinguish at the first current zero was determined. From these values of shunt resistance, the rate of rise of applied voltage was calculated by equation (3) and the curve of Fig. 6 was obtained.

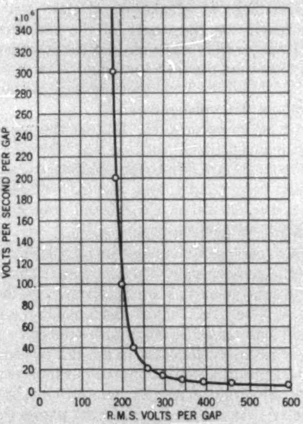

Fig. 6—Recovery of Dielectric Strength of Short Arcs in Air

For voltages per gap above 500 r. m. s. the mean rate of recovery of dielectric strength was $4 \times 10^6$ volts per sec. This seems to be very low compared to $25 \times 10^6$ volts per sec. observed by Golladay and Slepian for brass electrodes, but agrees better with the value calculated in section 7 thus indicating that air deionizes more slowly than zinc vapor. As the voltage per gap was reduced, the rate of recovery of dielectric strength increased reaching $300 \times 10^6$ volts per sec. at 180 volts per gap. For lower voltages per gap than this the rate of recovery could not be determined, as the arc would extinguish even when the shunting resistor was omitted.

The curve of Fig. 6 appears to have an asymptote at 165 volts r. m. s. corresponding to a peak of 235 volts. The normal cathode drop for copper in air is 252 volts.[6] Thus the conclusions of the preceding section are confirmed.

## 12. Long Arcs and Arcs in Slots and Holes in Insulating Materials

Equations (**14**) and (**15**) state that the rate of recovery of dielectric strength of the arc space measured in total volts applied per second is a constant. In deriving this relationship, it was assumed however that the linear dimensions of the cross-section of the arc space were large compared with the distance between the electrodes. This is certainly not the case for long arcs, or for arcs compelled to play in small holes or slots in insulating material.

When the space charge region before the cathode is long compared with the linear dimensions of its section, Poisson's equation in one dimension cannot be applied, and it is no longer true that the maximum electric gradient, at the cathode, is a function only of the total applied voltage as is given in equation (**8**). The boundary of the space charge region is no longer a plane parallel to the cathode surface, but it tends to run up on the sides of the hole or slot as in Fig. 7. This makes even an approximate analysis very difficult, but it is hoped to deal with this in a future paper. A first study indicates that the voltage across the space charge sheath is of the same order of magnitude as the impressed *gradient* multiplied by the thickness of the slot or diameter of the hole. Hence we would expect the arc to extinguish if during the transition there is an almost instantaneous application of a *gradient* of the order of two or three hundred volts divided by the hole diameter or slot width.

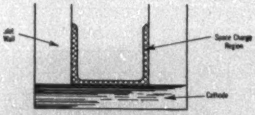

Fig. 7—Space Charge Region for Arc in Slot

The curve of Fig. 8 obtained by Mr. R. C. Mason for slots and holes in soapstone one to two inches long roughly bear out this conclusion. The gradients given are those at which the unshunted arc would just extinguish at the end of the first half cycle. If we multiply this gradient by the width of slot we get for the different slot widths the following:

1/16 in. slot, 143 volts
2/16 in. slot, 146 volts
3/16 in. slot, 92 volts
4/16 in. slot, 63 volts

These are all at least of the right order of magnitude. Mr. Mason's results show that in narrow slot arcs can be interrupted in circuits of very considerably higher voltage than in the open air.

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[6] K. Rottgardt, *Ann. d. Phys.* Bd. 33, 1910, p. 1161.

## 13. THE OIL CIRCUIT BREAKER

The success of the oil circuit breaker in high power a-c. systems is probably due in part to all the factors discussed in the previous sections. Most important of all undoubtedly is the fact that the arc under oil is in an oxygen free atmosphere. Hence, in spite of the fact that quantities of hydro-carbon gases are produced by the decomposition of the oil, due to the lack of oxygen no persistent combustion flame follows the extinction of the arc at zero current.

The confining action of oil upon the arc raises enormously the impressed gradient at which the current can be interrupted, just as the narrow slots did as described in section 12. The arc plays in a hydrocarbon gas "hole" through the oil, and at the time the current is passing through zero this "hole" may be of relatively small section.

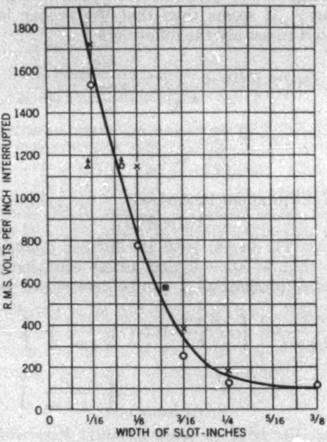

FIG. 8—EXTINCTION OF ARC IN SLOT

Another factor which is very likely of considerable importance is the electrical conductivity of the hot oil immediately adjacent to the arc, and which probably contains decomposition products. The conductivity of this oil may be very large just at the moment the arc extinguishes, although of course, it would fall off very rapidly as the hot oil mixes with the cold oil about it. No information is available as to the magnitude of this conductivity but it seems very probable that it is sufficient to influence appreciably the rate of rise of applied voltage during the extinction process, as considered in section 2.

Still another possible factor is the influence during the extinction period of drops of oil or the carbonized residues of drops of oil floating in the arc space. These particles will form centers for the ions to discharge upon, very much as the wires of the gauze sheets in the experiment of section 9. Space charges will form in the neighborhoods of these particles which will tend to relieve the region immediately adjacent to the cathode from the high gradient which it would otherwise have.

## 14. SUMMARY

The time interval allowed by the external circuit for the arc space to recover its insulating properties after a current zero, is important in the operation of an alternating switch. The low dielectric strength of an ionized gas is to be attributed to the non-uniform potential gradient caused by the development of space charges. Calculations with certain approximations lead to the conclusion that in the case of arcs which are short in comparison with the diameter of their section, the first one or two hundred volts of dielectric strength are recovered almost instantly while later increments of dielectric strength are recovered at a rate lying between one million and one hundred million volts per second. Experiments have been carried out substantiating this conclusion.

For an arc which is long with respect to the diameter of its section the manner of recovery of its dielectric strength is not so simply stated. It is probably nearly correct to say that the ability to withstand a certain electric gradient is recovered almost instantly, and that later increments of dielectric strength return more slowly. The magnitude of this gradient varies in an inverse manner with the linear dimensions of the section of the arc as shown by experiments of Mason.

Experiments of Neher and others have shown the possibility of increasing the rate of recovery of dielectric strength by causing the arc to pass through holes in metal plates or the openings in metal gauze sheets.

A continuing chemical activity in the gases from an arc may cause the persistence of low dielectric strength for times long in comparison to those predicted by the preceding theories.

The success of the a-c. oil circuit breaker is to be attributed to all the factors considered in this paper.

## 15. ACKNOWLEDGMENT

This paper gives an account of general ideas and principles developed on the extinction of a-c. arcs by a considerable number of men working with the author for the past few years. Many of the topics touched upon are of great interest in themselves, and it is hoped that they will be elaborated upon in later papers by the men who have carried on the work. Besides the men already mentioned in the paper, those who have contributed largely to the topics discussed are B. P. Baker, R. C. Dickinson, G. H. Cole, and F. C. Todd, but first and foremost should be mentioned A. C. Crago, who in spite of his untimely death in 1925, continued to influence the work through the wealth of ideas and inspiration he left behind him.

## Appendix

### MATHEMATICAL TREATMENT OF EXTINCTION OF AN ARC MOBILITY OF POSITIVE IONS CONSIDERED

The arc space will be considered as consisting of two sharply defined regions, as in Fig. 4. One, next to the cathode contains only positive ions. The other, the rest of the gas space, contains positive and negative ions in equal numbers.

Let $l$ = thickness of cathode region at time $t$.
$i$ = current density at time $t$.
$V$ = potential at point distant $x$ from cathode at time $t$.
$X = -\dfrac{\partial V}{\partial x}$
$v$ = velocity of positive ions toward cathode at point $x$.
$k$ = mobility of positive ion.
$e$ = electronic charge.
$n$ = density of positive ions in cathode region at point $x$.
$n_0$ = density of positive ions in body of gas at time $t$.
$n_{00}$ = initial density of positive ions.
$\alpha$ = coefficient of recombination of ions.
$B$ = rate of increase of impressed voltage.
$V_0 = B\,t$ = potential impressed on electrodes.

In the cathode region we have the following relations:

$$i = n\,e\,v \qquad (1)$$

$$v = k\,X = -k\frac{\partial V}{\partial x} \qquad (2)$$

$$\frac{\partial^2 V}{\partial x^2} = -4\,\pi\,n\,e \qquad (3)$$

the displacement current, $\dfrac{1}{4\,\pi}\;\dfrac{\partial X}{\partial t}$ being neglected.

Eliminating $n$ and $v$ from these equations and integrating,

$$\frac{\partial V}{\partial x} = \sqrt{-\frac{8\,\pi}{k}\,i\,x + A} \qquad (4)$$

where $A$ is a constant of integration. Substituting (4) in (3) we get

$$n = \frac{i/e}{k\sqrt{-\dfrac{8\,\pi\,i}{k}\,x + A}} \qquad (5)$$

In the main body of the gas we have

$$\frac{d\,n_0}{d\,t} = -\alpha\,n_0^2 \qquad (6)$$

Integrating this gives

$$\frac{1}{n_0} = \frac{1}{n_{00}} + \alpha\,t \qquad (7)$$

If $n_{00}$ is very large (7) becomes

$$n_0 = \frac{1}{\alpha\,t} \qquad (8)$$

The neglecting of the displacement current in equation (**1**) is probably justified except near the boundary of the space charge region adjacent to the body of the gas. Here, we have space charge constantly being freshly exposed by the motion of the space charge boundary, and the conduction current is correspondingly reduced. In the main body of the gas, however, the displacement current is again zero, and the conduction current is the total current, and not very different from the conduction current in the space charge region away from the space charge region boundary. It seems then that the proper boundary conditions to use are the following:

$$n_0 = n\,(l) = \frac{i/e}{k\sqrt{-\dfrac{8\,\pi\,i}{k}\,l + A}} \qquad (9)$$

$$\frac{d\,l}{d\,t} = \frac{i}{n_0\,e} \qquad (10)$$

Last, if the gradient in the body of the gas is negligible,

$$V_0 = V\,(l) \qquad (11)$$

Applying (**11**) to (**4**) with the further boundary conditions that $V\,(0) = 0$ and using equation (**9**), the constant of integration $A$ can be determined leading to

$$V_0 = \frac{k}{12\,\pi\,i}\left\{\left[\frac{8\,\pi\,i}{k}\,l + \left(\frac{i}{k\,e\,n_0}\right)^2\right]^{3/2} - \left[\frac{i}{k\,e\,n_0}\right]^3\right\} \qquad (12)$$

(**12**) together with (**8**) and (**10**) and $V_0 = B\,t$ form a complete system of equations for determining $l$, $n_0$, and $i$. The solution is

$$l = \frac{\sqrt{B}}{\left[\dfrac{\alpha}{12\,\pi\,k^2\,e}\left(\left[1 + \dfrac{8\,\pi\,k\,e}{\alpha}\right]^{3/2} - 1\right)\right]^{1/2}}\,t$$

$$i = \frac{\sqrt{B}}{\left[\dfrac{\alpha^3}{12\,\pi\,k^2\,e^3}\left(\left[1 + \dfrac{8\,\pi\,k\,e}{\alpha}\right]^{3/2} - 1\right)\right]^{1/2}}\,\frac{1}{t} \qquad (13)$$

$$V_0 = B\,t$$

The maximum gradient, $\dfrac{\partial V}{\partial x}$, which occurs at $x = 0$ is given by

$$\left(\frac{\partial V}{\partial x}\right)_0 = \left(\frac{12\,\pi\,e}{\alpha}\;\frac{1 + \dfrac{8\,\pi\,k\,e}{\alpha}}{\left[1 + \dfrac{8\,\pi\,k\,e}{\alpha}\right]^{3/2} - 1}\right)^{1/2}\sqrt{B} \qquad (14)$$

If we assume as in sections 4, 5, and 6 that there is a definite critical breakdown gradient $G$ for the gas, we have for the rate of recovery of dielectric strength,

$$B = \frac{\alpha^2}{144\,\pi^2\,e^2}\left(\left[1 + \frac{8\,\pi\,k\,e}{\alpha}\right]^{1/2} - \left[1 + \frac{8\,\pi\,k\,e}{\alpha}\right]^{-1}\right)G^2 \qquad (\mathbf{15})$$

Changing to practical units we have for $B$ and $G$ in volts per cm., and $k$ in cm./sec. per volt/cm., and letting $e = 4.77 \times 10^{-10}$ e. s. u.

$$B = 1.02 \times 10^{13}\,\alpha^2\left(\left[1 + 3.59 \times 10^{-6}\,\frac{k}{\alpha}\right]^{1/2} - \left[1 + 3.59 \times 10^{-6}\,\frac{k}{\alpha}\right]^{-1}\right)G^2 \qquad (\mathbf{16})$$

Substituting in numerical values we may take for air at normal pressure and temperature, $\alpha = 7.6 \times 10^{-6}$ (from section 5) $k = 1.4$[7], and $G = 30{,}000$. This gives $B = 3650 \times 10^6$ volts/second.

At 940 deg. (as in section 5) taking $\alpha$ as varying inversely as the cube, and $G$ inversely as the first power of the temperature we have $\alpha = 1.06 \times 10^{-7}$, and $G = 7100$. As for $k$, according to Phillips,[8] and Kovarik,[9] the variation will be as the first power of the temperature and so at 940 deg., $k = 6.2$. With these values (**16**) gives $B = 81 \times 10^6$ volts per sec.

At 1200 deg. we have $\alpha = 4.8 \times 10^{-8}$, $G = 5600$, and $k = 7.5$ giving $B = 15.6 \times 10^6$ volts per sec.

## Discussion

**R. W. Sorensen:** These figures given in Fig. 1, which are primarily theoretical figures, to show what happens across an arc, have been checked by us in the laboratory and we get figures of the same form.

Under oil the voltage across the arc is around 150 to 250 volts on an ordinary 200,000-volt breaker. The voltage across an arc in rather high vacuum is only of the order of about 12 to 13 volts, occasionally as high as 20 volts. The amount of energy to be accounted for can be measured by these voltages encountered and shows quite a difference, one being approximately ten times the other.

A phenomenon of interest shown by some oscillograms I have seen may make some other modifications of some of the work here. Under some conditions the current goes out before it crosses the zero line. In other words, you don't have to get down always to zero current apparently to have the arc go out.

That introduces another phase. If the long arc gradients could be eliminated by reducing all the arcs to short ones, this would not only tremendously simplify the theoretical problem, as Dr. Slepian has pointed out, but would also simplify actual operation. The work which he has suggested, which he and his associates are doing, in getting around these long arc gradients by means of holes through metals, et cetera, certainly will be of great value to us.

**R. M. Spurck:** Mr. Slepian's paper brings out a number of points as characteristics of the a-c. arc that have been recognized and studied by all circuit breaker designers for a number of years.

Two points impressed me. (1) The rate of voltage increase of the arc voltage after the voltage or current has passed through zero is one of the factors tending to cause a reestablishment of the arc. This rate of voltage reestablishment varies widely in different systems. (2) The tendency to reestablish the arc may be reduced by artificial means.

From an oil-circuit-breaker standpoint this means that if the tendency of the arc to reestablish is reduced a shorter arc length is obtained. This shortening of the arc length reduces the amount of gas formation in the breaker during its operation and the reduction in the amount of gas formation results in a reduction in duty on the breaker.

Consider first the rate of the rise of the reestablishment of the arc voltage. Inasmuch as it is dependent on the system and generator characteristics it is not, in general, usually practical to lighten the duty on the breaker by changing the system or generator characteristics. Neither is it possible from a practical standpoint to analyze a system and determine the rate of voltage reestablishment so that a breaker of light duty can be put on some systems and a heavier breaker put on systems having more severe duty.

It is, therefore, necessary to design an oil circuit breaker so that it will operate under the worst conditions of reestablishing voltage that any practical system can produce. The effect of reestablishing voltage also serves to explain why oil circuit breakers perform well in some locations and not so well in others.

Consider next the question of artificially reducing the effect of the reestablishing voltage on prolonging the arc. One of the artificial means suggested by Mr. Slepian was the use of shunt resistors across the circuit-breaker terminals. This he discards as impractical from a regular operation standpoint, and I quite agree with him.

Another way of artificially reducing the effect of the reestablishing voltage or the arc length under definite conditions of arc-voltage reestablishment is to increase the insulation strength of the arc stream by cooling or by pressure. In practise this has been done for a number of years by the use of the explosion chamber which utilizes the gas formation from the arc to increase the pressure around the arc stream and to blast cool oil through the arc stream. The efficacy of this device has been proved by many tests and wide experience.

**C. D. Ainsworth:** With the advent of high-potential alternating current came the oil circuit breaker. The principles of the earlier air-break circuit breaker designed for the older d-c. circuits crept into or influenced the design of this new device to such an extent that even today we are confronted with recommendations and demands for mechanical speed of break that involve us in designs that must expose to a high-power, high-voltage arc vast areas of oil. There must result, in addition to the destructive pressures during each succeeding cycle of arc, the excessive volumes of hydrocarbon gas which produce those pressures,—volumes of gas superheated, highly ionized but slowly deionizing, diffusing with relative slowness into the oil and thereby tending to prolong the cycles of arc which produce them. On the other hand, visualize an oil circuit breaker with an increased number—even a multitude—of shorter series arc gaps, each gap exposing a minimum of oil area and a maximum of electrode area and volume to the arc. Over the surface of the electrodes, by inter-reaction, the arcs are propelled to new and cooler zones. At the current zero, the arc zone is cooler, and the slowly de-ionizing hydrocarbon gases of the high-speed break are to a large extent replaced by the more quickly de-ionizing metal vapor of the electrodes.

That such a breaker—one in which a much greater proportion of the thermal energy of the power arc is absorbed and converted by the electrodes—approaches the desideratum of Dr. Slepian's paper is apparent. Initially it has the advantage derived from the condition of lower temperature as set forth in Dr. Slepian's equation (**13**) on page **4**:

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[7] *Handbuch d. Physik*, Vol. XXII, page 323.

[8] P. Phillip, *Proc. Roy. Soc.*, London A., Vol. 78, 1906, p. 167.

[9] P. F. Kovarik, *Phys. Rev.*, Vol. 30, 1910, p. 415.

$$n = \frac{1}{\alpha t}$$

which equation is another way of stating that the number of ions, or the ionic density, varies directly as the cube of the absolute temperature. It follows, with the lower temperature and the correspondingly smaller number of ions, that the rate of recovery of the dielectric strength will be much more rapid, particularly where the more rapidly de-ionizing metal vapor is, as here, in greater proportion. Finally, the increased number of arc gaps, shorter in comparison to the electrode diameter, affects a condition of reduced space charges and consequent increase in rate of recovery of dielectric strength,—this is in addition to the 200-volt equivalent increments of dielectric strength instantaneously recovered at each gap.

Such an oil circuit breaker, however, is not a design of the future. Refined and perfected in the present, it is essentially a development of the past. The multi-break oil circuit breaker with energy-absorbing arcing contacts, under test and in the field has already demonstrated the fact that it does approach the desideratum of Dr. Slepian's paper.

**J. B. MacNeill:** The paper deals with means of opening circuits radically different from those now in use. Time will tell the degree to which these ideas can be incorporated in commercial apparatus. It may be said, however, that present methods in many cases are not considered altogether adequate, and there are individual switching problems where the application of the ideas dealt with in this paper seem entirely feasible. The oil circuit breaker has been developed far beyond the expectation of the original sponsors of the device and in general is giving adequate protection on all high-voltage or high-power a-c. systems. Any oil-immersed device, however, has the inherent disadvantage due to the oil content, and substitutes for oil immersed devices will always receive any consideration they may deserve.

**F. W. Maxstadt:** (communicated after adjournment) Dr. Slepian's contribution is of interest and great value in another field than the one pointed out in the paper.

Comparatively little has been known about the mechanism of the arc used in electric arc welding, either a-c. or d-c. It is now clear that the persistence of the a-c. welding arc which operates well below 165 r. m. s. volts cannot be due to residual ionization, but must on the other hand be caused by chemical activity which is known to be oxidation of iron vapor. The fact that the arc reestablishes itself in the same path after a current zero seems to me to prove that the chemical activity extends into practically every region of the arc volume. This easily accounts for the included impurities in the deposited metal.

The well known fact that arcs between iron electrodes in an atmosphere of hydrogen require voltages in excess of 165 r. m. s. shows that chemical activity in the arc stream is, under such conditions, too small to provide a mechanism for arc reestablishment.

This suggests a line of investigation to find a gas or mixture of gases which will provide chemical activity for restarting the arc at low voltage (for safety to the operator) and yet produce no harmful compounds in the deposited metal.

The same analysis applies to the d-c. arc which oscillograms show has unsteady characteristics, with current values approaching zero for an instant and suddenly building up to normal, aided of course by the reactive voltage of the series choke put into the circuit for the purpose.

Dr. Slepian's analysis of the time-phase relations between the arc current and voltage shows that successful arc-welding circuits must have sufficient series inductance, low series resistance, low condensance (capacity) between turns of the transformer or choke and high shunt resistance across the arc. Even the conducting vapors which surround the arc, but do not take part in the arc itself, are a cause of its extinction.

# Civilization and the Engineer

## President's Address

### BY BANCROFT GHERARDI

What has the engineer contributed to civilization? Have his contributions been major factors in its development? It is important that we should know the answers to these questions, for sooner or later the standing of the engineer in the world in which we live depends upon these answers. To get them it is necessary to consider the development of civilization.

From the earliest days, mankind's primary need has been food. He cannot exist without it. In addition, in most climates he must have shelter, clothes, and fuel. As long as all human energy had to be devoted to meeting these needs, no margin remained for the improvement of man's condition, either physical, mental, or spiritual. It is to the extent that there is a margin of effort available after the minimum of these requirements is provided that civilization may develop. The existence and magnitude of such a margin has depended upon man's willingness and ability to produce beyond this minimum and the aids that he has in his work. The margin beyond that necessary for maintaining existence goes to the improvement of his status.

The students of the early stages of man's development measure the steps by which he has advanced by certain outstanding factors. Accepting the classification of Lewis H. Morgan, these are: the development of speech; the use of fire; the bow and arrow; the manufacture of pottery; the domestication of animals; the development of writing. In these, we find the beginning of civilization. And we find something more; something of the deepest significance to the engineer. Fire,—first used for warmth and cooking, and now our principal source of power. The bow and arrow—a machine by means of which man can apply his strength and dexterity more effectively. Pottery,—a manufactured article to minister to his household needs. Domestic animals,—a source of power under the control of man and a more reliable supply of food and clothing. Although at that time scientific knowledge was unknown, invention probably not recognized as such, and engineering not even dreamt of, in the bow and arrow and in pottery all were foreshadowed.

The struggle by man to learn the facts of nature and to utilize them has been slow and extended over ages. As we look back, at times progress has seemed to halt, and generally, there was no definite conception of what constituted progress or in what ways it should be sought, but nevertheless, the ground work was being laid and man was slowly moving forward.

There gradually grew up an appreciation that Nature was not whimsical or beyond understanding; that she has hidden treasures—materials and forces—that could be used by man if he would but learn what they were; that Nature was an inexhaustible treasurehouse if man would but find the "open sesame," the way to use her resources—and that the "open sesame" was to learn of Nature by studying her and not by trying to speculate what she should be; that we may theorize if our theories are based on facts and checked by experience, but that speculations without facts are idle dreams and that nothing that may be determined by observation may be safely accepted except as it is so determined. Early there were such minds,—Euclid, Archimedes, Aristarchus, Hipparchus,—but in their time they did not represent the common method of thought even of the educated people.

Then came a long period of halting, "the dark ages," during which not only did progress seem to cease, but in many cases it was discouraged by powerful authorities. But the greatest darkness always comes just before the dawn.

In the 16th and 17th centuries, the scene began to change rapidly. A number of wonderful men of whom I shall name only two, Galileo and Newton, devoted their lives to the study of nature, that is, to the getting of facts and to the effort to develop theories that would be consistent with these facts, and which could be used to postulate other facts which, if verified by observation, further extend knowledge. These men were the pioneers in our modern civilization. To these and to their successors in theory and application we owe the developments that constitute the determining factors of modern civilization.

And what are the characteristic features of the material aspects of modern civilization? They are power and machines.

Power by which man power and horsepower are multiplied to practically any extent that may be desired, and machines which, when driven by power, will make or do numberless things which man may desire. At last it is possible for man, aided by power and machinery, to produce so far beyond the primary needs of food, shelter, clothes, and fuel, that not only can he greatly improve the quantity and quality of these, but provide numberless other conveniences, comforts, and luxuries; and these results are attained today with shorter working hours than formerly were necessary to achieve a much lower standard of living.

These results have been a direct outcome of the work of the scientist, the inventor, and the engineer. And to these should be added other groups engaged in the practical application of science,—such as chemists, biologists, doctors, and architects. They have been

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*Presented at the Summer Convention of the A. I. E. E., Denver, Colo., June 25-29, 1928.*

contributed to also by the promoter, the manager, the banker, and the capitalist—all necessary factors in the development of modern civilization but without the products of science, invention, and engineering, they could not have builded as they have. For not only is our modern civilization based upon science and its applications but these have furnished the capital necessary to realize the results attained. For capital is the margin between what we produce and what we consume for our day-by-day needs, and this margin is mostly due to the applications of science. Suppose that today China should decide that it should have transportation and a communication system equivalent in proportion to its population to that of the United States. How would it go about getting such a system promptly? There is no way that it could do so. In material and labor, this system would cost say 200 billion dollars, for highways, railroads, motor cars, and telephone plants. This could not be borrowed, because aside from any question of credit, there is no such surplus available in the rest of the world; it is not to be had, because so much has not been saved in its whole existence of several thousand years.

This brief outline of the development in the material aspects of modern civilization indicates sufficiently the part that has been taken in it by the scientist, the inventor, and the engineer. I have confined myself largely to the material aspects because the very nature of engineering has to do with physical things. Should it be inferred that the engineer has made no contribution to the mental and spirtual advance of mankind? The facts by no means justify such a conclusion.

Consider the printing press and its relations to the diffusion of knowledge. The phonograph and what it has done for music. The moving picture, and now the talking movie and their part in education and entertainment. Radio broadcasting and its bringing millions in direct touch with the finest orchestras, the greatest educators and entertainers, and enabling millions to hear the President of the United States when he speaks on a public occasion. The farm telephone and the automobile and what they have done to break down the isolation of farm life. Is the world's great transportation system—railroads, motor cars, and steamships—used solely for business? Has travel ceased to have an educational value since the slowness, expense, and discomforts of the stage coach and of the sailing ship have been eliminated from it? And our communication system—mail, telephone, and telegraph—does it contribute nothing to our higher life? Is it never used except in relation to the material aspects of life?

If such contributions to our mental and spiritual development were all that have been given to the world by the engineer and his allies, they would be notable and more than refute the statement sometimes made that the engineer's contributions are solely materialistic. But this is by no means all.

The development of culture requires leisure from the struggle for existence. Was Athens the poorest nation in the world when it developed its wonderful literature and arts? It was materially the richest of its time. Was Florence, when it developed its school of painting, a poor and struggling city? Quite the reverse. Do we look today to Patagonia or Tasmania or to the Esquimos for high mental and spiritual development? We should if material welfare was inconsistent with spiritual and mental attainments. History justifies the statement that material, mental, and spiritual development as a whole go together, and that while a genius may develop under almost any conditions, a high and distributed culture is favored by a high and distributed material welfare. The scientist and engineer have sometimes done themselves injustice in assenting to statements and occasionally even suggesting, themselves, that they have not contributed except to the material welfare of the world.

Still another outgrowth of the development of science and of its application is the educational system of today. Not always is it realized that for the maintenance of our present educational system in this country, it is a necessity that there should be a sufficiently high standard of living to permit of the withdrawal from the immediate production of the necessities of life the hundreds of thousands of teachers who are directing this educational work and the millions of students who are taking part in it. It is also necessary that there should be available huge amounts of capital to be expended for the provision of buildings and other necessary equipment. All of these have been rendered possible only by the results of applied science in increasing the margin over and above that necessary for existence.

From the beginning of history, man has constantly struggled to improve his economic status. He has wanted an assured supply of food and more pleasing food, more comfortable and better lodging, more comfortable, better, and a greater variety of clothes, better shelter, more comforts of all kinds, more leisure and recreation, and now, through the tapping of the resources of nature, year by year and decade by decade, he is attaining these ends more and more, not only for the favored few but for the great mass of the people who, but a few decades ago, were believed to be condemned by the very nature of life in this world to an existence limited to the barest necessities. This sweeping change in the economic status of individuals and nations has given rise to many questions of a fundamental character. These questions have to do with social relations, education, economics, business, health, politics, and religion. They comprehend the whole relationship of man to man and of man to his environment.

These questions do not depend for their solution upon engineering principles which so largely rest upon the characteristics of physical and inanimate things, but they have to do rather with people and with human reactions. This, however, does not take them out of the field in which the engineer must be skilled to do his work. For even though the engineer's main duty lies in the control of nature, the very organization of society which that control has given us means that the engineer, in his engineering work, must operate as a part of organized society and conduct his relations with others with due regard to human reactions. The conquest of nature on a large scale must be done by those who can use organizations of men. The modern engineer should have as great a capacity for human management, cooperation, and for dealing with others as the men in politics, religion, and other professions which are devoted primarily to the study of man. To the extent that the engineer can measure up to these requirements he may become a leader in other fields of action, as well as being a leader in his own.

Whatever may be the part of the engineer in the solution of these questions, his principal work and that which only he can do well, is to take the scientific facts made available by the scientist and, by their adaptation to practical ends, add to the welfare of mankind. And can we engineers, notwithstanding the stupendous advances of the 19th century and the gigantic steps forward of the first quarter of this century, doubt that still greater opportunities lie before us year by year, as with pride in the service that we render mankind and humility that so little has been done and so much remains to be done, we continue our work devoted to making this world a better and easier one to live in so that the burden of life may be lifted more and more from the shoulders of the average man.

# The Diverter Pole Generator

BY E. D. SMITH[1]

Associate, A. I. E. E.

*Synopsis.—This paper describes a new type of generator developed to overcome certain limitations inherent in the shunt and the compound generator, when used for charging batteries by the constant potential, the modified constant potential, and the floating methods.*

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THE advantages of the constant-potential, the modified constant-potential, and the floating method of battery charging are quite generally recognized. These systems require a source of direct current of constant voltage.

The following characteristics are desirable in a constant potential battery charging generator:

1. It should preferably have a flat voltage curve which does not rise with increasing current at any point, otherwise stability of the correct charging voltage cannot be maintained without manual adjustment.

2. It should operate safely as a motor without speed-up or polarity reversal during feed-back from the battery.

3. It should preferably have a slight rise of voltage with decreasing current near zero load as a means for curbing a tendency to swing over to discharge during light loads.

4. When floated on bus-control circuits, which are subject to heavy momentary loads, at some point above full load the voltage should abruptly droop to protect the generator from the high peaks by shifting them to the battery, otherwise the generator will be damaged.

5. After the occurrence of these peak loads the generator voltage should return to its original value.

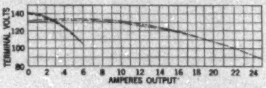

FIG. 1—VOLTAGE REGULATION CURVES OF 1½-KW. 130-VOLT SHUNT AND COMPOUND GENERATORS

———————— increasing load shunt generator
- - - - - - - - - - - decreasing load shunt generator
-.-.-.-.-.-.-. increasing load compound generator
-..-..-..-.. decreasing load compound generator

NOTE.—With shunt generator the voltage comes back slightly lower after an overload while the compound generators voltage comes back slightly higher after an overload

6. Commutation and efficiency should compare favorably with current standards.

The shunt generator is inadequate as its voltage falls too greatly with increasing load. Voltage regulators, when sufficiently sensitive, are necessarily delicate, and being susceptible to external conditions are difficult to keep properly adjusted.

The compound wound generator fulfils some of the conditions but has its limitations. In case of feed-back from the battery the generator will motorize and run at an excessive speed and thus may cause damage. This is due to reversed current in the series coils bucking the shunt winding and lowering the field strength.

Also, the voltage curve, Fig. 1, of a flat compound generator is too convex for constant potential battery charging. With this typical curve it is difficult to charge at any rate between zero and that corresponding to the maximum voltage point, unless resistance is interposed between the generator and battery. In fact, any reduction of the charging current below the value corresponding to maximum voltage will usually be followed by a downward surge to discharge.

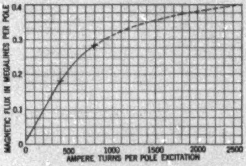

FIG. 2—MAGNETIZATION CURVE

———————— in producing the regulating flux in the diverter pole generator the magnetic changes are confined to the diverter pole and take place on this part of the curve
- - - - - - - - - - - in producing the regulating flux in the compound generator the magnetic changes occur in the main magnetic circuit and take place on this part of the curve

The voltage characteristic of the compound generator is curved, since the necessary magnetic changes produced by the series winding take place in the main magnetic circuit in accordance with the magnetization curve of the machine, (Fig. 2). Usually in obtaining satisfactory design it is necessary to work at least partly on the curved portion of the magnetization curve and the compound generator reflects this curvature in its voltage characteristic.

The following is a description of a generator designed for the specific purpose of meeting the exacting requirements necessary in a constant potential generator for battery charging:

In this generator, as shown in Fig. 4, a small diverter pole (1) spaced midway between the main poles, has a magnetic bridge connecting it to one of the main poles. Magnetic flux from the main pole will leak across this bridge to the diverter pole. A restricted section at 2

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[1] Rochester Elec. Products Corp., Rochester, N. Y.

*Presented at the Northeastern District No. 1 Meeting of the A. I. E. E., New Haven, Conn., May 9-12, 1928.*

in this bridge performs two functions: first, it limits the leakage, and second it serves as a magnetic choke, whereby it is possible to regulate the magnetism passing to the armature from the inner face of the diverter pole at 3. This regulation is possible since practically the whole of the main field ampere turns acting on the diverter pole are concentrated in overcoming the reluctance at this one restricted section, so that any reduction of the flux through this restricted section will release ampere turns expended here and raise the magnetic potential at 3 and consequently increase the magnetism passing to the armature at this point. At no load substantially all magnetic flux crossing the bridge will take the low reluctance path through the diverter pole (1) back to the frame without pausing through the armature. A coil in series with the load circuit surrounds the diverter pole. This coil, as the load current increases, opposes and reduces the passage of magnetic flux through the diverter pole (1) to the frame.

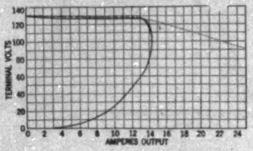

FIG. 3—VOLTAGE REGULATION CURVES OF 1½-KW. 130-VOLT DIVERTER-POLE CONTROL-BUS GENERATOR

———— increasing load self excited
- - - - - - - decreasing load self excited
. . . . . . . . . increasing load separately excited

NOTE.—The voltage comes back slightly higher after an overload

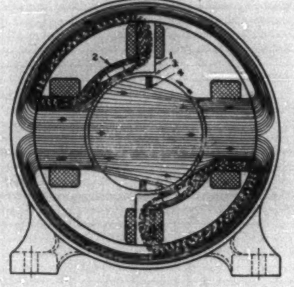

FIG. 4—MAGNETIC FLUX DISTRIBUTION AT NO LOAD

———— main flux
- - - - - - - leakage flux

The decrease of flux through the restricted section at 2, attending any reduction of flux through the diverter pole, (1), produces, as above stated, a rise in the magnetic potential at 3. The result is that part of the magnetic flux leaking across the bridge will take the air-gap path to the armature at 3 (Fig. 5), adding its value to the main pole flux and compensating for the voltage drop in the generator.

No variation of flux from the main pole to the armature occurs as there is no change in the magnetic potential at the main pole air gap. This follows, since neither the main pole nor the frame is highly saturated and the small variation of flux through these parts, due to the change of flux through the diverter pole, produces no appreciable variation in ampere turns of the main field excitation expended on this part of the main magnetic circuit.

A flat voltage curve is obtained since the magnetic changes produced by the series winding take place only in the diverter pole (1), and as the flux density here is kept low these changes occur on the low straight portion of the magnetization curve, thus eliminating most of the curvature from the generator voltage characteristic. These magnetic changes occurring in the diverter pole take place from a higher to a lower density on increasing the current output of the generator. This is the reverse of the occurrence in the compound generator, and the effect is to invert whatever part of the magnetization curve appears in the generator voltage characteristic, producing a concave instead of a convex voltage curve. By the proper adjustment of the diverter pole winding an almost straight curve is obtained with a slight rise on approaching zero load.

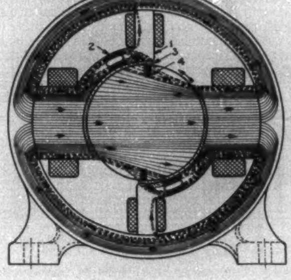

FIG. 5—MAGNETIC FLUX DISTRIBUTION AT FULL LOAD

———— main flux
- - - - - - - leakage flux

When motorizing, the main field strength is maintained substantially at its full value, as reversed current in the series coil can divert no further leakage due to saturation of the bridge restriction at (2). Also, any tendency for the diverter pole (1) to establish itself as an independent pole opposite in polarity to the main pole is limited to a safe value since the diverter pole already carrying the leakage flux quickly approaches saturation at any increase of flux through it, and safe operation as a motor is assured.

At some value of the load current the ampere turns on the diverter pole equal those on the main pole and at this time the magnetic flux leaking across the bridge to the diverter pole is all re-diverted across air-gap 3, and there is no further leakage flux for an increased current to re-divert to the armature.

What occurs when the load is increased beyond this point is best illustrated by some recent tests.

The machine tested was a 1½-kw. generator, designed for floating with a 129-volt bus control battery. For the tests, this generator was equipped with a pair of movable exploring brushes by which the voltage around the commutator could be checked step by step and the flux distribution determined.

Fig. 6 shows the flux distribution when the generator was operating with brushes up, shunt fields separately excited at a constant value and various currents passed through the diverter pole coils. This shows that the regulating flux is produced only at the diverter pole face, the flux from the main pole remaining practically constant.

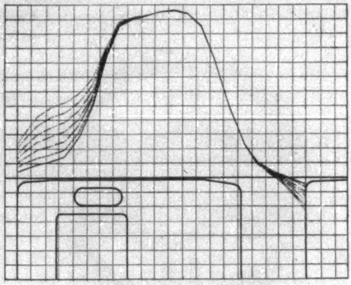

Fig. 6—Flux Distribution Curves

When excitation of diverter poles is increased, armature carrying no current, brushes up, with main fields separately excited at constant value

——————— 0 amperes in diverter pole coils
- - - - - - - - - - 5 amperes in diverter pole coils
-.-.-.-.-.-. 10 amperes in diverter pole coils
-..-..-..- 15 amperes in diverter pole coils
.......... 20 amperes in diverter pole coils
——— . . . . ——— 25 amperes in diverter pole coils
——— . . . . . ——— 30 amperes in diverter pole coils

Figs. 7 and 8 illustrate flux distribution under load, Fig. 7 showing flux changes up to the voltage cut-off point of 14 amperes. This shows the effect of armature reaction in the crowding of the main field to the right and in the partial suppression of the diverter pole field.

Fig. 8 shows that with any increase in the load current beyond the cut-off value of 14 amperes, instead of an increase in the diverter pole field there is a definite and decided collapse. With this collapse of the diverter pole field the terminal voltage falls and hence the main field excitation is reduced which accounts for the reduction of the main pole flux. The solid line of Fig. 3 shows the voltage regulation for this machine.

Fig. 9 represents flux distribution under conditions similar to those of Fig. 8 except that here the main fields were separately excited and maintained constant during the test. The broken line of Fig. 3 shows the voltage regulation for this machine.

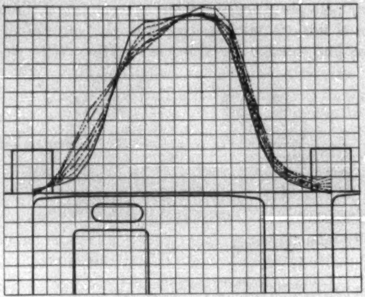

Fig. 7—Flux Distribution Curves

When output is increased up to the voltage cutoff point at 14 amp. with main fields self excited

——————— 0 amperes generator output
- - - - - - - - - - 3 amperes generator output
-.-.-.-.-.-. 6 amperes generator output
-..-..-..- 9 amperes generator output
-...-...- 12 amperes generator output
-....-.... 14 amperes generator output

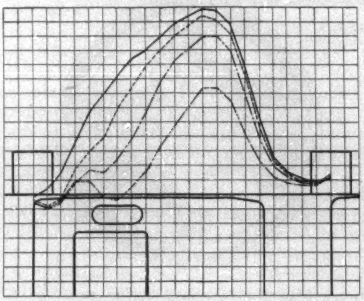

Fig. 8—Flux Distribution Curves

When diverter pole generator is loaded beyond the voltage cutoff point at 14 amp. with main fields self-excited. Although the load was increased the amperes decreased due to the falling voltage

——————— 14 amperes generator output
- - - - - - - - - - 14.4 amperes generator output
-.-.-.-.-.- 14 amperes generator output
-..-..-.. 11.2 amperes generator output

This test also shows the collapse of the diverter pole field when the load current is increased beyond the 14-ampere point at which the ampere turns on the diverter poles equal those of the main pole.

It appears from these tests that when the ampere turns on the diverter pole exceed those on the main pole, the flow of magnetism through the diverter bridge is reversed. Magnetism now flows from the diverter pole to the main pole and not from the main pole to the diverter pole. Under these changed conditions the magnetizing action of the armature assists the flow of magnetism through the bridge instead of opposing it. In fact, under heavy loads the magnetism does actually reverse and pass from the armature to the bridge, and joining with the main pole flux, passes back to the armature at the hindward pole tip, constituting cross magnetism, while the magnetism from the diverter pole crossing the bridge flows backward through the main pole to the frame returning to the diverter pole without passing through the armature.

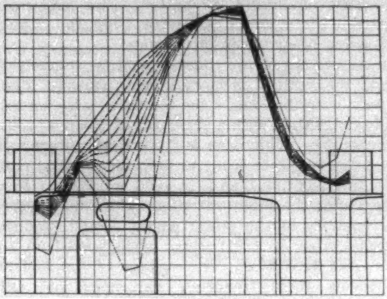

Fig. 9—Flux Distribution Curves

When diverter pole generator output is increased beyond the voltage cutoff point at 14 amp. with main fields separately excited at constant value

| | |
|---|---|
| ———— | 14 amperes generator output |
| --------- | 16 amperes generator output |
| -.-.-.-.- | 18 amperes generator output |
| -..-..-..- | 20 amperes generator output |
| -...-...- | 22 amperes generator output |
| -....-....- | 24 amperes generator output |
| -.....- | 26 amperes generator output |
| -......- | 28 amperes generator output |
| -.......- | 30 amperes generator output |
| -........- | 45 amperes generator output |

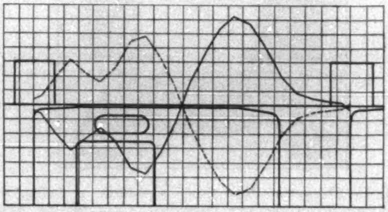

Fig. 10—Flux Distribution Curves

During short circuit of diverter pole generator with main fields self-excited. The flux pulsates between the values shown by the solid and broken line curves

This theory requires the co-existence of two opposite magnetic fluxes in the main pole and also in the frame. However, it is the only apparent explanation of the definite collapse of the diverter pole field occurring with each increase of the diverter pole ampere turns above those of the main pole.

Fig. 10 shows flux conditions during short circuit, the flux pulsating between the values shown by the solid and broken line, the voltage and current pulsating also between the positive and negative values of 0.7 volts and 19 amperes.

Fig. 11, which represents conditions when generator is operated as a motor, shows some distortion of the main field due to armature reaction and a slight reduction of the diverter pole field due to reversed current in diverter pole coils, this reduction being insufficient, however, to cause any instability in speed when motorizing.

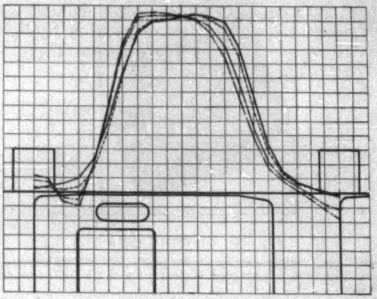

Fig. 11—Flux Distribution Curves

When diverter pole generator is operating as a motor with varying load

| | |
|---|---|
| ———— | 0 ampere output as generator |
| --------- | 3 ampere input as motor |
| -.-.-.-.- | 10 ampere input as motor |
| -..-..-..- | 15 ampere input as motor |

When the load on the generator decreases a descending excitation is produced in the diverter pole coils and due to the effect of hysteresis this descending excitation leaves a slight residual magnetic field passing from the diverter pole face to the armature. This accounts for the voltage being slightly higher after an overload than before, as shown in Fig. 3.

Good commutation is assured as the diverter pole provides a commutating field of the correct direction for improving commutation and this field varies with the current output as in an interpole generator.

The efficiency will equal that of a similarly rated compound interpole generator since the excitation on the main poles will equal the shunt and series excitation and diverter pole excitation will be the same as that of the interpole of the compound generator.

Figs. 12 and 13 illustrate the pole and the complete field assembly of the diverter pole generator.

The characteristics of this generator are desirable for many battery charging applications.

In telephone exchanges when floated in parallel with the main battery, the generator maintains the voltage within the close limits required for correct operation of the equipment and furnishes the current directly to the exchange without its passing through the battery. Considerable economy is effected by the saving of power and in the increased life of the battery, and also by a saving of labor through the elimination of the necessity of manual voltage regulation.

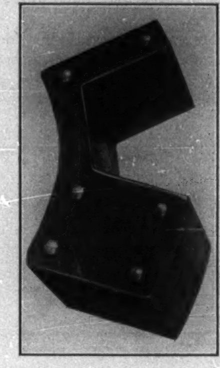

Fig. 12—Diverter Pole

The hole in the bridge does not appear as the two end laminations are punched without this hole the inner laminations have the hole as shown in Figs. 4 and 5

When several batteries are charged in parallel by the constant potential or modified constant potential method, as in recharging of vehicle and automobile batteries, the advantage of constant voltage, coupled with the ability to operate safely as a motor without polarity reversal or speed up during power failure is quite apparent.

In control bus operation, where a small generator is connected and operated continuously in parallel with a battery for switch operation, all of the desirable characteristics of this generator are utilized to advantage.

The flat voltage characteristic insures maintenance of correct floating voltage under varying load conditions with minimum supervision.

The ability to motorize safely without speed up or polarity reversal gives security during power interruptions.

The slight rise in voltage with decreasing current near zero load and the recovery momentarily to a slightly higher voltage after an overload combines to produce the desired stability of the correct floating voltage at the light load which constitutes the normal operating condition.

The sharp droop in the voltage just above full load amply protects both the generator and motor from danger of overload during switch operation.

The high voltage recovery after overload prevents the gradual diminishing of the generator voltage and consequent discharge of battery that occasionally happens with a shunt generator from the repeated overloading occurring in this service.

An advantage of the constant-voltage characteristic is that the battery is more quickly charged after it has been carrying load, since the battery is charged at a higher rate than with a generator of drooping voltage characteristic. This is an additional advantage as the higher charging rate tends to keep the battery, particularly the negative plates, in good condition. It also appears that the slight variations which may occur in the frequency of the power circuit should produce a beneficial effect in the battery when floated on a diverter pole generator. The voltage of the generator will follow these frequency variations and either slightly charge or discharge the battery as these variations are above or below normal. This will give a desired amount of activity to the negative plates without overcharging the positive plates.

It might appear that a generator with a drooping voltage characteristic is desirable for this floating method since the charging current is less affected by speed variations of the driving motor. However, as these generators are usually driven by induction motors their speed is not affected by variations in voltage, variations in frequency being the only cause of speed variation. Since the frequency of modern commercial power circuits is held within very close limits, no objectionable variation of motor speed is encountered which would justify the use of a drooping voltage generator for its damping qualities.

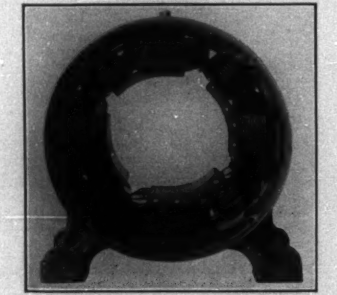

Fig. 13—Diverter Pole Field Assembly of a 7½-Volt Generator for Constant Potential Charging of Automobile and Radio Batteries

The battery discharge during switch operation is not so great where the diverter pole generator is used, since the generator supplies the current demand up to its full load capacity, while the shunt generator gives little assistance to the battery at this time. This means that a higher bus voltage will be maintained during switch operation with the same size battery when floated with a diverter pole generator.

In some power applications, as for instance, car retarder operation, the load demands, while still intermittent, are more frequent and of longer duration so that the equivalent continuous load is a greater percentage of the battery capacity.

In this case it is desirable to restore the battery charge as much as possible between the heavy demands and it is also desirable that the bus voltage be maintained under varying load so that uniform response will be assured at the various control stations.

The generator designed for this application absorbs all loads up to 200 per cent of its normal rating, maintaining constant bus voltage up to this point and the battery is only called into action during loads in excess of this value.

Several thousand of these generators have been built and are operating on various battery charging applications, and their performance has justified the conclusion that the generator has many advantages where the constant potential, modified constant potential, or the floating method of charging is used.

The outstanding feature of this machine is its ability to give constant voltage with varying load and still be safe from speeding up or polarity reversal during feedback from the battery. However, the other characteristics, *viz.*, the inverting of the voltage curve which makes for stability of the charging voltage, the high voltage recovery after overload insuring voltage stability on light loads, and the drooping of the voltage on overload which protects it from serious overloading, contribute to its adaptability to the battery charging field.

# An Amplifier to Adapt the Oscillograph to Low-Current Investigations

BY SIGMUND K. WALDORF[1]

Associate, A. I. E. E.

***Synopsis.***—*There has been need in several fields of electrical engineering research for a means to study time relations, wave forms, and similar phenomena where only infinitesimal currents are obtainable. The limitations and advantages of several possible methods of investigation are briefly compared, and the conclusion reached that the ordinary oscillograph can be most profitably adapted to such work.*

*The best form of vacuum tube amplifier for the work is then discussed, followed by a description of the steps taken in the design of a suitable resistance coupled amplifier. This amplifier is then described.*

*The results of tests showing quality of reproduction are given in the form of oscillograms and a characteristic curve. The recommended procedure to be followed and the necessary precautions to be observed in the use of the amplifier are given, with a short discussion of the abilities and possibilities of the oscillograph in its widened field of usefulness.*

* * * * *

## INTRODUCTION

THE ordinary type of oscillograph, operating on the D'Arsonval principle, has proved of great value in many fields, but the currents required to give workable deflections are so large as to restrict its use to cases where the available currents are greater than approximately a twentieth of an ampere. To obtain fairly large deflections, about a tenth of an ampere is necessary for alternating currents and almost a fifth for continuous currents. For low current investigations, where the currents are less than these values, one must look around for other means or apparatus to meet the requirements. The cathode ray oscillograph or the Einthoven string galvanometer might be mentioned, but they have several serious limitations for engineering problems for which the usual type of oscillograph has desirable characteristics. For combined sturdiness, ease of operation, transient recording, simultaneous multiple recording, and general utility the oscillograph far surpasses these other instruments.

Thus it has been thought worth while to adapt the oscillograph to small currents by means of a suitable vacuum tube amplifier. Such amplifiers are in common use for many purposes, so that their various forms and principles of operation are now widely known. The particular problem in this case was to obtain perfect reproduction over the entire frequency range of the oscillograph, a requirement calling for the careful selection of the proper circuit and careful subsequent design and construction. An amplifier circuit utilizing transformers cannot be expected to give perfectly equal amplification of all frequencies over a wide range. This can be predicted from theoretical considerations and has been shown experimentally in the unpublished effort of another investigator using a resistance coupled amplifier with a transformer in the output circuit. The purpose of this transformer was to obtain sufficient oscillograph current without requiring excessive plate current from the output vacuum tubes.

With this in mind, the resistance-capacity coupled and the straight resistance coupled amplifiers are the only ones that can be expected to give faithful amplification over a wide range of frequencies, so these were the only two seriously considered here. As will be seen later, the resistance coupled circuit was the only one found to be entirely satisfactory for all frequencies for which the oscillograph can be used, and it has the additional advantage that it amplifies continuous currents as well as alternating. The amplifier which has been built and is described in this paper will therefore meet all frequency conditions for which the oscillograph is applicable.

## PRELIMINARY DESIGN AND TESTS

After it was decided to try the resistance-capacity coupled amplifier first, a survey was made to determine which of the many kinds of available vacuum tubes were best suited to the purpose. The Western Electric 102-D and 104-D tubes were thought to be the most desirable. Their nominal ratings as furnished by the manufacturer are given in the following table.

VACUUM TUBE RATINGS

| | 102-D | 104-D |
|---|---|---|
| Normal filament current (amperes.) | 0.95 | 0.97 |
| Normal filament voltage | 2 to 2.5 | 4 to 5 |
| Normal filament voltage | 2 to 2.5 | 4 to 5 |
| Normal plate voltage | 100 to 150 | 100 to 150 |
| Normal grid voltage | 0 to − 3 | −15 to − 30 |
| Normal plate current (milliamperes) | 0.3 to 1.5 | 10 to 30 |
| Plate-filament impedance (ohms) | 40000 to 100000 | 1500 to 3000 |
| Amplification constant | 26 to 34 | 2 to 3 |
| Maximum safe plate voltage | 160 | 160 |

The plan for the amplifier was to place the input on the grid of a 102-D tube and have the plate circuit of

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*Initial and Best-Paper prize paper, presented at the Meeting of the Baltimore Section, District No. 2, Baltimore, Md., April 22, 1927.*

this tube act on the grids of a number of 104-D tubes with their grids, filaments, and plates connected in parallel. The oscillograph element was to be connected directly into the combined plate circuit of these 104-D tubes. As no transformers were to be used anywhere in the circuit because of possible distortion, the 102-D tube was chosen for the first stage for its high amplification constant, and the 104-D tubes for the second stage for their high current output at relatively low plate voltage. As it could be seen that the plate current requirements of the output tubes would be severe, the parallel arrangement in the output stage was called for. The power requirements of both these types of tubes are not exceptional and can be handled easily.

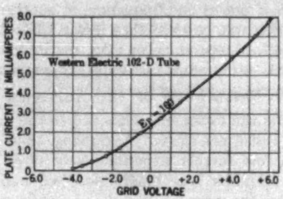

Fig. 1—Typical Characteristic of a Western Electric 102-D Vacuum Tube with Negligible External Plate Impedance. Plate Voltage = 160

The characteristics of the two types of tubes were taken with the plate milliammeter the only external plate impedance, holding the applied plate voltage constant at the maximum safe value (160 volts). These characteristics are given in Figs. 1 and 2. The characteristic curves of the 102-D tube were then taken with appreciable external plate impedance to determine the proper resistance to give a perfectly straight characteristic. After a few trials, a plate impedance of approximately 25,000 ohms was found to be the proper value, giving a straight characteristic for negative grid potentials between zero and approximately three and a quarter volts. Under these conditions the voltage variation across the plate impedance was slightly more than 28 volts, as calculated from the plate impedance and the change in plate current.

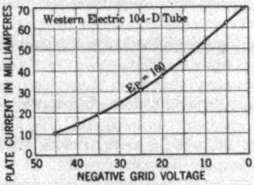

Fig. 2—Typical Characteristic of a Western Electric 104-D Vacuum Tube with Negligible External Plate Impedance. Plate Voltage = 160

The characteristics of the 104-D tubes indicated that these tubes would give straight line reproduction in use if the total grid voltage variation did not exceed a maximum value of 30 volts, varying from − 3 to − 33 volts.

A resistance-capacity coupled amplifier was then made up using the connections of Fig. 3. This was in two stages—the first designed for voltage amplification with the 102-D tube, and the second for maximum possible current output with two 104-D tubes in parallel. The bias on the first stage was − 1½ volts and that on the second was varied from − 15 to − 22½ to determine the most suitable value. The plate impedance of the first tube was two lavite resistance units in series, of 25,300 ohms total resistance. The two-microfarad coupling condenser was an ordinary telephone condenser of waxed paper and tinfoil. The grid leak was ordinarily 100,000 ohms of lavite resistors, but was varied from about 140,000 to about 40,000 ohms to find the best value. Other necessary information is given in the diagram of Fig. 3.

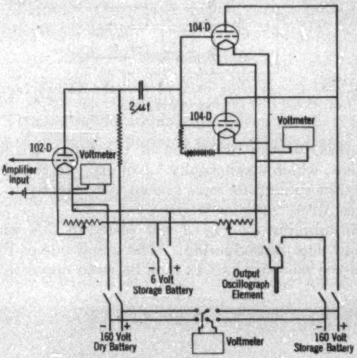

Fig. 3—Connections of the Trial Resistance-Capacity Coupled Amplifier

To test the quality of reproduction of the amplifier, it is necessary that the input wave form be recorded as well as that of the output, and that the input as indicated by the input oscillograph element be absolutely the same as that impressed on the amplifier input. To attain this, the input connection shown in Fig. 4 was used for all tests of reproduction. The 57- and the 355-ohm resistances were tube rheostats used as a potential divider to give the desired voltage across the 4-dial resistance boxes. This voltage was read on a General Electric Type P3 voltmeter with a 30 volt range. The resistance $R_G$ was zero in the earlier tests but had values up to 105,000 ohms in the tests of reproduction of the final amplifier. Its function in the input grid circuit will be explained later.

In order that all the conditions of testing should be known in the earlier work, a sine wave was used for the input. The potential divider was adjusted to give exactly 21.2 volts on the 30-volt voltmeter, which gave a peak value of 30 volts across the 4-dial resistance boxes. This gave a total voltage variation across these boxes of 60 volts between opposite alternating wave peaks. For example, in the first test it was desired to have an input grid variation of exactly three volts. Using 20 ohms per volt based on peak values, $R_1$ was dialed to 30 ohms and $R_2$ to 569 ohms. This value of $R_2$ allows one ohm for the resistance of the input oscillograph element, which was actually 1.5 ohms. In this manner, the input conditions were known very exactly to be the desired three volts variation.

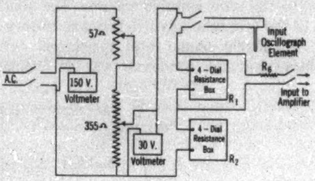

FIG. 4—CONNECTION USED TO IMPRESS KNOWN INPUT ON THE AMPLIFIER

The amplifier of Fig. 3 was tested in this way and showed poor reproduction. The amplitude of the output wave was only half an inch between opposite peaks, and showed a decided flattening effect on waves of one side and a peaking effect on those of the opposite side.

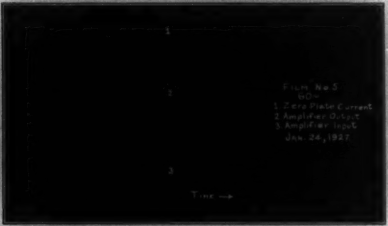

FIG. 5—DISTORTION OF A 60-CYCLE SINE WAVE BY THE OUTPUT STAGE OF THE TRIAL RESISTANCE-CAPACITY COUPLED AMPLIFIER

To determine which stage of the amplifier was responsible for the distortion, the first stage was removed and 30 volts grid variation placed directly on the 104–D tubes through their coupling condenser and grid leak. To increase their plate output, a third tube was added in parallel to the other two, and the three operated under these conditions gave an amplitude of approximately an inch. The distortion was still decidedly present, as can be seen in Fig. 5. The straight line marked "1" on this oscillogram was obtained when the output oscillograph element was disconnected from the output plate circuit and no current flowed through it.

Further similar trials were made with this form of amplifier, investigating the effects of various values of coupling condensers, grid leaks, grid bias, and variations of grid input potential. But even at relatively small amplitudes the distortion was very apparent, if not at one frequency, at another. Finally the decision was reached that it was quite hopeless to attain perfect reproduction over the desired range of frequencies using resistance-capacity coupling.

### FINAL FORM OF THE AMPLIFIER

Utilizing the experience obtained in the experiments on the resistance-capacity coupling, and with the aid of a few further experiments, a plain resistance coupled amplifier was finally designed and built according to the plan of Fig. 6. As there are several interesting features included in this amplifier, it will be described in some detail.

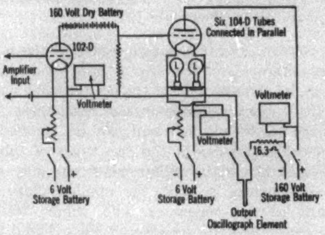

FIG. 6—FINAL FORM OF THE PURE RESISTANCE COUPLED AMPLIFIER

It is necessary that each stage have its own set of filament and plate batteries. The battery requirements of the first stage are not unusual. The filament voltage of the 102–D tube is kept at 2.25 volts and draws about 0.9 ampere filament current. A 6-volt filament storage battery is used simply for convenience, as the usual commercial storage battery has three cells. Naturally, a 4-volt battery would be just as satisfactory for the purpose. The plate battery for this stage is seven blocks of the usual 22½-volt radio B batteries. Using fresh batteries, the plate voltage is very close to 160 volts. These batteries should maintain this voltage for considerable time as the current drain is only a little over a milliampere.

The battery requirements are much more severe in the second or output stage. The current drain on the 6-volt filament storage battery is 6.25 amperes when the filament voltage is held at the fixed operating value of 4.5 volts. The filament rheostat is two 15-in. lengths of No. 18 advance wire, suspended together in parallel between two porcelain insulator knobs. The slider is a 15-ampere battery clip with a lead from the negative battery terminal. One end of the resistance wires is connected to the common negative filament lead.

The plate battery is a heavy-duty radio storage battery with a current rating of a quarter of an ampere. This battery has a number of end cells so that the voltage can be maintained at 160 volts. When the amplifier is in operation, the terminal voltage of this battery falls off two or three volts due to the internal resistance of the cells. When the additional plate impedance was placed in series with the output oscillograph element, this was kept in mind. If the storage battery were of sufficient capacity to maintain constant voltage, this extra resistance would be made greater than 16.3 ohms. Because of this slight voltage variation, it has been found desirable to have the plate voltmeter connected across this battery all the time it is in operation, so that the plate voltage may be noted at any time.

The added plate resistor of 16.3 ohms was found necessary to help straighten the characteristics of the 104–D tubes. As it must carry as much as a quarter ampere it is made of No. 24 double cotton-covered advance wire wound non-inductively on a wooden spool. A further aid in straightening the characteristic is the potential divider arrangement of the two incandescent lamps *LL* in series across the tube filaments. When under operating conditions the maximum plate current is drawn from each tube, the plate current is of the order of seven per cent of the normal filament current. If all this flows into the filament at one end there will be excessive heating of the filament at this end. There will then exist an appreciable change of the filament temperature with change in plate current, causing an irregular amplifier characteristic. Providing two parallel paths for the plate current reduces this effect to a minimum by giving a more even division of the current between the two ends of the filament.

Using a potential divider of two 200-watt, 120-volt, Mazda C lamps as shown, actually improved the operation of the amplifier considerably. Of course, besides having the effect described, these lamps are additional resistance in the output circuit, thus serving a double purpose. The lamp resistance varies with the applied voltage, but with the constant filament voltage maintained, their combined series resistance was found to be fixed at about 15 ohms.

The negative grid bias on the 102–D tube is 1.6 volts furnished by a single small flashlight cell. No bias battery is needed on the 104–D tubes; the proper bias is furnished by the drop across the plate impedance of the 102–D tube. The voltage drop across this plate impedance ranges from 4.9 to 33.1 volts in the working interval. This impedance is 24,500 ohms pure resistance of two lavite cylinders in series.

To reduce to a minimum inductive and capacity effects which are troublesome at the higher frequencies, the amplifier has been made as compact as possible. The amplifier itself, with its tubes, lamps, resistances, and miniature filament voltmeters, is all mounted on a board 25 by 12 in. The dry B batteries, the two filament and the input switches, and the plate voltmeter (of the regular larger size) are on the table supporting the amplifier board. The total table space used is 29 by 34 in., which allows space to spare. The two filament storage batteries and the plate storage battery are placed on the floor beneath the table. Provision has also been made to charge the filament storage batteries easily by the use of double-pole, double-throw switches in place of the single-throw filament switches of Fig. 6. To avoid unimportant complications, these connections have not been shown on the amplifier diagram. Otherwise, the amplifier is as simple as the diagram indicates.

## TESTS OF REPRODUCTION

The performance of an amplifier under all possible conditions must be, necessarily, the criterion of its worth. This particular amplifier has been tested under a number of differing conditions and has been found to have excellent properties.

As the amplifier is to work with the oscillograph, all tests were made considering the combination as a single unit designed to record low-current phenomena. The conditions on the oscillograph as well as those on the amplifier were kept under close observation. For all tests, the tensions on the oscillograph elements were kept at five ounces, and when observations were made, the galvanometer field current was kept at the rated saturation value of 0.35 ampere or slightly above.

Resistance coupling is a d-c. amplifier circuit and permits of taking a static characteristic curve. This was done, (for results see Fig. 7) where the sensitivity of the output oscillograph element was 40 milliamperes per centimeter deflection. As can be seen, straight line reproduction is obtained for grid potentials between zero and $-3.2$ volts, with a total change of oscillograph deflection of 5.2 centimeters. With a grid bias of $-1.6$ volts on the input, operation takes place in the middle of this range. In tests where the input wave form is unknown, the amplitude is kept well within these limits, so that any peaks present will not be distorted by being beyond the straight portion of the curve.

The static characteristic curve brings out an interesting property of this amplifier, which is that the amplifier cannot be seriously overloaded. This is due to cut-off occurring in either the first or second stages when the input grid potentials become excessive. The phase of the input is reversed in the output, that is, an increase of input grid potential decreases the output current. If the input grid is given an increase in potential, the plate current of the 102–D tube increases with a consequent decrease in the potential of the 104-D tube grids. This decreases the output current. If the input voltage is too high, the output grids become sufficiently negative to cause close to cut-off in the 104-D tubes. If the opposite condition should occur, the input grid becoming strongly negative, the plate current of the 102-D tube will be very small and the output grids will approach zero potential, which they cannot exceed. This limits the output current to that which the 104-D tubes furnish with zero grid potential. Although this may damage the oscillograph element if left on for any time, the amplifier should not be affected.

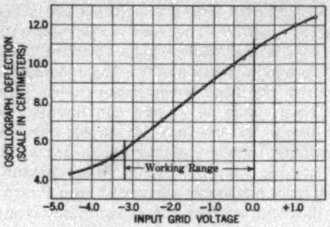

Fig. 7—Characteristic of the Combined Vacuum Tube Amplifier and Oscillograph

Tests were made with alternating currents over a wide range of conditions. It is here that the resistance $R_G$ in the input grid circuit serves an important purpose. (See Fig. 4) This was given values from zero to 105,000 ohms. If the grid currents were of the same order of magnitude, or even somewhat smaller than the currents to be amplified, there would be distortion introduced when the grid circuit impedance is made very high. The effect of this grid impedance is not noticeable for any values within these limits. The oscillograms shown are with this high resistance inserted. This amount was used because the author was most interested in the behavior of the amplifier when the currents to be amplified are of the order of five to ten microamperes, or larger. With these small currents the necessary circuit resistance to be inserted to obtain proper input grid potential variations is of about the stated value. If it is desired to amplify smaller currents than this, or the available voltage variation is too low to give good oscillograph amplitude, a third stage may be placed on the amplifier, identical with the 102-D stage and acting on this stage with the necessary change of grid bias. Under such conditions the input voltage variation need be only little more than a third of a volt and the amplifier currents possibly of the order of a microampere for maximum amplitudes.

Fig. 8—Reproduction of a 60-Cycle Sine Wave

Figs. 8 and 9 show the quality of reproduction of the amplifier with a sine wave impressed. The straight lines on these figures are the zero lines of the input voltages; no zero lines were taken on the output. The amplitudes of the output waves are two inches, which is about the limit for perfect reproduction. It should be borne in mind that the relative amplitudes of the input and output waves have no significance, as the size of the input wave depends on the ohms per volt in the four-dial resistance boxes of the input connection, whereas the output wave depends upon the input grid voltage variation.

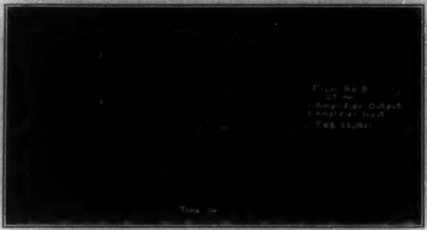

Fig. 9—Reproduction of a 25-Cycle Sine Wave

Fig. 10—Reproduction of a 58-Cycle Alternating Wave of Irregular Form

Fig. 10 shows the reproduction of an a-c. wave with slot ripples present on the peaks; Fig. 11, a fairly smooth wave taken at a higher frequency, where the wave forms of the cycles varied. The amplitude on Fig. 10

is 1¾ in. between opposite peaks; that on Fig. 11 is 1½ in.

Fig. 12 is of special interest as this is a record of a transient phenomenon of very irregular wave form. As the form of the wave was unknown, when the record was being made, the amplitude of the light spread of the oscillograph was widened until it was about 1½ in., by increase of the resistance across which the input was connected. This allowed ample room on the straight portion of the amplifier characteristic for any peaks that might have been present and not apparent on the stationary ground glass scale. Then the film was exposed and the record obtained. The arrow points to a short oscillation which occurred and which was reproduced very well. As this oscillation is at about 4500 cycles and is amplified satisfactorily, it is indicated that the amplifier will take care of all conditions which the oscillograph itself can handle properly at the higher frequencies.

FIG. 11—REPRODUCTION OF A 135.5-CYCLE ALTERNATING WAVE OF VARYING FORM

A careful study of these tests shows that the amplifier described gives identical reproductions and that it is competent to extend the range of the oscillograph down to five or ten effective microamperes at one effective volt on alternating current, or slightly higher voltage on direct current.

FIG. 12—REPRODUCTION OF A VERY IRREGULAR TRANSIENT ALTERNATING CURRENT

The arrow indicates the presence of a damped oscillation of approximately 4500 cycles per sec.

## PROCEDURE AND PRECAUTIONS

A few words should be said concerning the actual use of the amplifier. It is believed that it has been reduced to its simplest possible form and that apparatus requiring the operator's attention is at a minimum. The observations and tests described have been made by a single operator without difficulty. The ordinary care exercised in the use of the oscillograph and of vacuum tubes should be sufficient for the proper operation of the combined amplifier and oscillograph.

FIG. 13—ACCENTUATION OF HIGHER HARMONICS BY THE AMPLIFIER DUE TO UNDULY LONG PLATE BATTERY LEADS

Whenever the amplifier is used, the input grid battery and the dry cell plate battery should be tested to see that their voltages are correct. The grid battery, especially, should be watched and not allowed to get below approximately 1.54 volts. If the maximum amplifier output is to be obtained at all times, it has been found advisable to hold this grid bias close to 1.60 volts.

FIG. 14—AN APPLICATION OF THE AMPLIFYING OSCILLOGRAPH TO A HIGH-VOLTAGE D-C. INVESTIGATION

The filament and plate storage battery voltages should be kept as close to the proper values as convenient. Slight changes in these have not been found to cause distortion if such changes do not occur during the interval when the film is being exposed.

As mentioned previously, if a storage battery is available for the plate supply of the 104-D tubes which has sufficient capacity to maintain its voltage, the value of the additional resistance in the output circuit must be made greater than 16.3 ohms by about 8 ohms. Of course the exact value must be determined by experiment in any particular instance.

To lengthen tube and oscillograph element life, the output circuit should be closed only so long as is necessary for proper adjustments and observations. It is advisable also to turn off the filaments of the vacuum tubes as soon as convenient.

An interesting effect of unduly long leads is illustrated in Fig. 13. When not in use on the amplifier, it was desired to use the plate storage battery for other work, so about 150 ft. of insulated twisted pair were run from the battery to the other apparatus in question. Shortly after this had been done, the test of reproduction was made which is shown in Fig. 13. The irregularities of the input are much exaggerated in the output, indicating over-amplification of the higher frequencies. This new development in the amplifier was puzzling until the presence of the additional long leads came to mind. They were removed and the reproduction returned to its former good quality. The explanation of this effect is that the long twisted leads acted as a by-pass condenser across the plate battery for the higher frequencies.

An instance of the usefulness of the amplifier is given in Fig. 14, which is a test made to observe the commutator ripple of a high-voltage d-c. generator when shunted by condensers. Some research was in progress for which it was desirable to determine what could be done to remove the ripple of a 15,000-volt machine. The oscillograph was the logical means to employ for observation of the ripple, but as the oscillograph ordinarily requires about a tenth of an ampere for such indications, it is difficult to obtain and handle resistance for this current and voltage to be placed in series with the oscillograph element. So a suitable resistance, taking about three milliamperes at the given voltage, was connected across the generator and the amplifier input connected to a four-dial resistance box in the tail circuit. For this work a negative input grid bias of about three volts was used and the input so connected as to make the input potential more positive for increased applied voltages. The distance between "1" and "2" on Fig. 14 represents 5800 volts. Thus the oscillographic study was made very easily at a number of different voltages with the amplifier, which would have been very troublesome otherwise.

## CONCLUSION

It was the purpose of this work to develop a simple and convenient method for making oscillographic studies of high-voltage and low-current waves and similar phenomena—one which could be depended upon to give perfect reproduction of very small currents, preserving them in their true phase relations as well as in form. It is felt that this has been accomplished and that the amplifying oscillograph, if the combined amplifier and oscillograph may be so called, should prove a useful instrument in electrical engineering research. The oscillograph, already valuable in a wide field, has now had its range extended down to currents of about ten microamperes or less.

## ACKNOWLEDGMENT

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